# Development of a time/temperature logging device to characterise the burning characteristics of biofuels

by
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# Declaration

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# 1. Abstract

A lab scale combustion unit was designed, in order to characterise the performance of various woody and wood-based biofuels commonly used for energy production, cooking and heating. The unit was constructed in a way that it could be repeatedly reused and provide similar testing conditions, such as airflow for all samples. The requirements were that it was big enough to contain a fire large enough to yield good time/temperature profiles and at the same time easy to handle, operate and clean. It also had to allow the insertion of the thermocouples and flue gas probe.

Time / temperature profiles were obtained and $O_2$, $CO_2$ and CO levels in the flue gas determined for each biofuel. The samples consisted of the five most commonly used fuel wood species in the Western Cape, namely Rooikrans, Camelthorn, Bluegum, Black wattle and vine stumps and five processed products, namely wood pellets, wood briquettes, commercial charcoal, commercial briquettes and handmade briquettes. Combustion time/temperature profiles were obtained for all samples and characteristic values, such as the maximum temperature and coal temperature compared. This allowed an indication of which product performed better than others in the different combustion phases and is more suitable for different requirements, such as industrial heating, or domestic cooking. Even though Bluegum and Camelthorn performed best overall they were not necessarily suited, for example, for large scale industrial use. It was found that wood pellets and charcoal were the best biofuel for industrial purposes, whereas Rooikrans was found to be the best option for small scale use.

# 2. Opsomming

‘n Laboratoriumskaal verbrandingseenheid was ontwerp vir die toets en karakterisering van verskeie houtgebaseerde biomassa soorte algemeen in gebruik vir energie opwekking, kook en verhitting. Daar was besluit om ‘n eenheid te bou vir herhaalde gebruik wat die omstandinghede vir elke toets konstant kan hou, bv. ‘n damper om lugvloei deur die sisteem the beheer. Die eenheid moet groot genoeg wees om veilig ‘n groot genoeg vuur the bevat waarmee ‘n goeie tyd/temperatuur profiel verkry kan word, maar terselfdetyd klein genoeg wees om te hanteer, operateer en skoon te maak. Die eenheid moes ook voorsiening maak vir die insteek van die termostate en gas peilstif.
Tyd/temperatuur profiele is verkry en $O_2$, $CO_2$ en CO vlakke in die uitlaatgas is bepaal vir elke bio-brandstof. Die monsters was saamgestel uit vyf van die mees algemeen gebruikte brandhout spesies in die Wes Kaap, naamlik Rooikrans, Kameeldoring, Bloekom, Swartwattel en wingerdstompies, asook vyf geprosesseerde produkte naamlik houtpille, houtbrikette, kommersiële steenkool, kommersiële brikette and handgemaakte brikette.

Verbranding tyd/temperatuur profiele is verkry vir al die monsters en verteenwoord waardes is daarvan afgelees, bv. die maksimum temperatuur wat bereik is of die temperatuur waar die vlamme uitgesterf het en slegs koolhitte gemeet word. Hierdie profiele het dit moontlik gemaak om te identifiseer watter produk het beter gevaar as ander gedurende die verskillende verbrandingsfases en is beter gepas vir verskillende gebruike, bv. huishoudelike kook en verhitting. Resultate het gedui dat die Bloekom en Kameeldoring die beste gevaar het oor all die toetse heen, maar was nie noodwendig ideaal vir elke spesifieke doel nie. Dit was bevind dat die steenkool en houtpille die beste gepas is vir industriele gebruik en dat die Rooikrans beter geskik is vir huishoudelike en kleinskaalse gebruik.

# Acknowledgements

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# Table of contents

# List of figures

# List of tables

# 1. Introduction

Large parts of rural South Africa remain highly reliant on biomass for domestic heating and cooking fuel. Biomass for this purpose is often collected from surrounding wooded areas and is seen as a freely available source of fuel to sustain large communities. The problem with this type of harvesting is that it may result in deforestation, land degradation and desertification (Hoogwijk *et al*. 2005).

In 2007 it was estimated that 20.5% of all households are reliant on wood for cooking (Mabaso 2007). Mostly this wood is collected from surrounding areas and may impact heavily on the environment. Several commercially available stove designs are catering for these domestic needs, for example the rocket stove (Mabaso 2007), which was used to cook food in 13308 schools in South Africa in 2007, utilizing an estimated 25866 t of biomass, which is only a third needed for open fire cooking. These products are optimised to use as little wood as possible to maintain the cooking heat for a long enough time.

Another product aimed at rural communities is the WataCooka (Burger 2010), which combusts biomass waste to heat, cook and boil water. It is constructed to have a high draft through the system, which results in high temperatures to radiate and heat to the surrounding environment (heating) and the cooking surface. As the air moves through the chimney it heats water in a surrounding water tank.

All these products aim to provide energy and high functionality to people working or living in areas without electricity connection (Burger 2010).

In the industrial sector biomass combustion is used to fire kilns and boilers, sometimes together with coal in a process called co-firing. Often these processes require wood pellets as they are uniform in size, easy to transport and feed into the furnace. The preparation of these pellets is cost intensive and uses mostly commercial wood waste from forestry or sawmilling operations, rather than e.g. invasive tree species (Van Loo and Koppejan 2008).

Depending on the end use, different types of biomass with different characteristics are required. Industrial boilers and kilns typically need to obtain high temperatures for long periods, whereas informal households need lower temperatures for shorter times - e.g. just above 100$^{o}$C for cooking/ heating.

The aim of this project was to test the combustion performance of various wood and wood-based biofuels and compare burning times and temperatures that can be achieved. This allows the determination of the fuel that has the best potential to be used in an industrial setup or is more suitable for domestic cooking/heating purposes.

To date little research has been performed on the combustion characteristics of different wood fuels commonly used. Most studies comparing woody biomass refer only to calorific values in order to indicate their energy potential.

Combustion studies typically use sophisticated reactor vessels, where process variables, such as airflow, biomass feed speed (kg/h), biomass preheating and heat recirculation (Van Loo and Koppejan 2008) can be controlled and varied and the elemental composition of the combustion products can be analyzed (Bushnell *et al*. 1989). Usually they do not determine the combustion performance of the biofuel with regards to parameters, such as burning temperature and time.

The determination of combustion performance together with the major emissions (CO and $CO_2$) will allow an optimization of the biofuel use depending on the specific end use, availability and price and will indicate which material should be used for optimum energy output with minimal environmental impact or costs.

To determine combustion profiles, a small, custom built unit was developed, in which a predetermined amount of ovendry fuel was combusted. The temperature was recorded at four different positions as a function of time. Flue gas analysis was conducted at critical points during combustion in the chimney, measuring $CO_2$, $O_2$ and CO levels. In addition to the information on waste gas emission, these parameters also indicated whether complete combustion took place or not.

The combustion time/temperature profiles of the different biofuels were compared with regards to maximum temperature, the time this temperature was maintained and the time and temperature of the coal burnout. The biofuels were then rated according to their performance in similar conditions.

# 2. Theoretical Background

## 2.1 Wood-based biofuels in South Africa

Biomass remains an important energy source in South Africa even though it is a semi-arid country with very little forest cover (Winkler 2005). Nevertheless, woody biomass is used to provide energy for industrial and domestic energy. Large scale combustion utilizes wood and pulp waste to fire kilns and generate steam (Demirbas 2004). In some cases, electricity is generated on site and is highly dependent on the ability of the mills to supply biomass residues from the processing of logs continuously.

Poor rural households depend on wood and vegetative matter collected from surrounding areas for heating and cooking. An estimated 7 million tons of wood are burned in South Africa annually (Davidson *et al*. 2006). The connection of rural communities to the electric grid is still not complete, leaving them reliant on informally collected and traded fuel sources. This  makes it difficult to estimate the extent of usage as well as the effect on health and the state of biodiversity in these areas (Howells *et al*. 2005).

The use of biofuels in an unsafe manner is the cause of many household fires,which claim many lives. The volatile organic compounds (VOCs) along with particulate matter (soot) are the cause of many long term physical ailments, informally known as “hut lung”. This is a general term that refers to respiratory diseases, such as Tuberculosis, respiratory infections and cancer Women are affected at a higher rate as they are more exposed to emissions while going about their chores (Boman *et al*. 2006).

The effect on biodiversity and loss of habitat has far reaching consequences for the unique biodiversity that South Africa is known for. The most affected areas have seen the total loss of some rare bird and mammal species that inhabited the woodlands that were illegally harvested as fuel sources (Du Plessis 1994). Further problems with erosion and decrease of soil quality led to the formation of various initiatives like the Working for Water program, Working for Eergy program, clean fires campaign and the national biodiversity strategy and action plan (DEA 2010) trying to reduce the need for wood by rural communities.

These initiatives include the production of pressed briquettes and pellets from wood waste generated by industry and foliage collected around the houses. Many of these products are low in production cost and can provide an additional income for households (McDougal *et al* 2001).
These biofuels generally perform well and can be made in different ways to allow for different needs, like slow burning for heating or fast burning for cooking. These initiatives have shown promise but are not yet being implemented on a large scale.

## 2.2 Coal vs. biomass combustion

When comparing woody biomass to coal it becomes clear why coal has been such a popular energy source in the past. Depending on its quality it has a much higher calorific value - of around 33 MJ/kg (Wood and Baldwan 1985) - than wood, which is typically between 18 and 20 MJ/kg (Munalula and Meincken 2009). Its ash is also less alkaline, reducing the risk of fouling problems in the combustion chamber. Table 1 shows some properties of coal and different biomass resources (Demirbas 2003). These properties become very important when using these types of biomass commercially. The high ash content in coal may cause problem in furnaces whereas the high amount of fixed carbon contributes to the high energy content. Also the various metal oxides may be hazardous to the environment and can also cause problems within the combustion setup.

| | $Si_2O$ | $Al_2O_2$ | $TiO_2$ | $Fe_2O_3$ | CaO | MgO | $Na_2O$ | $K_2O$ | $SO_3$ | $P_2O_5$ | Cl |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Coal | 42.0 | 20.0 | 1.2 | 17.0 | 5.5 | 2.1 | 1.4 | 5.8 | 5.0 | – | – |
| Red oak wood | 49.0 | 9.5 | – | 8.5 | 17.5 | 1.1 | 0.5 | 9.5 | 2.6 | 1.8 | 0.8 |
| Wheat straw | 48.0 | 3.5 | – | 0.5 | 3.7 | 1.8 | 14.5 | 20.0 | 1.9 | 3.5 | 3.6 |

| | Moisture (% of fuel) | Ash (% of dry fuel) | Volatile matter (% of dry fuel) | Fixed carbon (% of dry fuel) |
|---|---|---|---|---|
| Coal | 4.8 ± 2.6 | 8.3 ± 1.5 | 2.4 ± 5.9 | 43.6 ± 3.8 |
| Oak wood | 6.5 ± 0.8 | 0.5 ± 0.1 | 78.6 ± 3.8 | 21.5 ± 2.1 |
| Wheat straw | 7.3 ± 1. | 12.7 ± 3.6 | 64.0 ± 5.1 | 23.4 ± 2.5 |

Table 1: Physical and chemical properties of typical biofuels

## 2.3 Woody biomass characterised in this project

*Acacia mearnsii (Black wattle)*

One of the most popular firewood species in South Africa, it is an extremely fast growing and invasive species that is found all across the country. The species was originally imported from Australia and can grow up to 25 m in height with a spreading crown and thick branches. Its density of around 570 kg/m$^3$ (Raliselo 2003) makes it an ideal biofuel source. The multiple uses of the tree extend past the use for firewood: its foliage can be used to improve soil quality where crops are grown and its bark yields valuable tannins that can e.g. be used for the manufacturing of resins and glues (Anon 1980).

*Acacia cyclops (Rooikrans)*

The name Rooikrans is derived from the shape of the seed and like the black wattle, considered a highly invasive species. Originally imported from Australia for its ability to handle salt spray and sand blast it was utilized to help stabilize the shifting dunes of the Western Cape. Since then it has spread to most coastal regions of South Africa and is harvested as a popular fire wood. The wood is relatively dense (750-800 kg/m$^3$) and rarely exceeds 20 cm in diameter. Another less commercial use include animal fodder from its seeds (Anon 1980).

*Eucalyptus sp. (Bluegum)*

The name Bluegum is a general term for a variety of eucalyptus species populating South Africa, which was derived in all likelihood due to the difficulty in distinguishing between some of these species. The wood has a lower density and calorific value than acacias, but is a great ignition source, once fully dried, due to the oils it contains. Originally used as mine supports the wood is also popular in the pulp and paper industry. The species is further seen as the backbone of South Africa's honey industry. The drawback in cultivating eucalyptus is that it is highly water intensive (it has been used in the past to dry up marsh land).

*Acacia erioloba (Camelthorn)*

The name camel thorn is derived from the preference that giraffes (known in Afrikaans as Kameelperde) show towards its leaves. Having a very high density (963 kg/m$^3$) it is excellent firewood. The species is endemic to South Africa and found is the semi-arid Northern Cape and Bushveld regions. It is protected from over-harvesting, but in many cases Camelthorn has been decimated by the informal fuel wood industry. Problems with diseases have caused further concern in some parts of the country (Raliselo, 2003).

*Vitis vinifera (Vine stumps)*

A by product of the wine industry in the Cape region, large quantities of vine stumps are commercially sold as fire wood. The drawback is their low calorific value (18.73MJ/kg) and density (around 597.37 kg/m$^3$) (Munalula 2009), which reduces their potential for utilization in a larger setup.

*Commercial Charcoal*

Charcoal is the product of incomplete combustion of wood and it is manufactured by burning biomass in an oxygen starved environment. It is less dense (around 200 kg/m$^3$ according to Evans and Emmons 1977) than coal briquettes and produces large amounts of CO when burned, as well as being difficult to handle (they break easily and produce black dust).

*Coal Briquettes*

Briquettes are made from refined and compressed charcoal. They are easier to handle due to their uniform size. The higher density of around 800kg/m$^3$ (Richards 1989) increases its burning time and reduces the amount needed, for example, to cook with. They are generally more expensive than charcoal and wood because of the additional processing.

*Wood pellets*

Mostly used in industrial kilns and boilers, these pellets have become a popular alternative fuel source as they can be made from most wood and biomass residues. They are produced by compressing small particles into a cylindrical shape of about 4-8 mm in diameter with typical densities of 650 kg/m$^3$ (Kofman 2007). The heat generated by the compression plasticize the lignin in the particles and bonds them together, leaving the pellet with a hard, shiny surface. They generally burn fast releasing large amounts of heat. The small size eases the transportation as well as the feeding process into furnaces or boilers.

*Wood briquettes*

These products are commonly sold as fuel source for cooking and heating to a small market. Their large size and weight makes them unpopular for large scale industrial use, but they are a viable option for the individual user. They are easy to produce and can contain almost any biomass material. They are formed by compressing small particulate biomass to cylinders with a specific density of up to 1200 kg/m$^3$ (Grover and Mishra 1996) and diameters of about 8 cm. A cylindrical hole in the center helps to improve drying and combustion efficiency (McDougal *et al.* 2001).

*Charcoal made from wood waste and soil*

Pyrolysis of wood waste in a small scale, low cost setup produced charcoal, which was then ground to a powder and mixed with soil acting as a fire retardant (to increase the burning time and reduce the max. temperature). This blend was pressed into briquettes and dried in the sun. The aim was to see what effect the addition of soil had on the burning rate and temperature of the charcoal briquette.

## 2.4 Combustion

Combustion is defined as the burning of a fuel, in this case biomass, along with an oxidant to produce heat and/ or work and includes various thermal, hydrodynamic, and chemical processes (Chenn 2010). The combustible material is ignited with an external heat source and the fuel and oxidant chemically interact towards a self sustained reaction:

Air + Fuel → Heat + $CO_2$ + $H_2O$ + NOx

By modifying the combustion parameters (e.g. air flow) one can alter the process to create different by-products and various systems have been developed to harness the different products of combustion, such as heat, or higher grade combustion fuels, such as coal or methane.

In recent years the concern over pollution and efficient use of the energy supply have changed the way we look at the combustion process. Research in engineering, thermodynamics and material science now focus on using the energy created by these processes to its fullest potential, as well as minimizing the negative impact on its surrounding environment (Chenn 2008).

Many factors affect the fuel performance in combustion, including:

- Elemental composition
- Physical properties (e.g. density, size)
- How the fuel physically and chemically responds to the heat.
- Availability of oxygen
- Heat transfer to the combustion area

- These factors should be kept in mind when trying to explain why some fuels perform better than others under the same conditions.

When trying to define the different stages of combustion one need to realise that all three the phases will possibly happen simultaneously, although it is possible to indicate, which phase is more prominent at a certain time.

*Drying or preheating phase:* For biomass to ignite, the temperature needs to be sufficiently high to maintain the combustion process. The required temperature (flash point) depends on the thermal properties of the fuel and how it retains the heat applied to it. Moisture causes heat loss and delays ignition, because energy is spent on the evaporation of water. In the initial phase an external ignition source is needed to raise the temperature of the fuel to its flash point. The flash point is the temperature at which the heat starts to interact with the macromolecules and volatile components are released. Most of these degradation products escape as gases after reacting with oxygen. The external heat increases the pyrolysis effect and causes the formation of tar that degrades into combustible vapours. At this point most of the combustion takes place indirectly meaning that volatile vapours only ignite after they are released from the wood. The wood itself has not yet started a self sustained combustion process.

*Degassing or gaseous phase:* When the temperature reaches the fire point the gaseous mixture is ignited and produces heat and light (flames). The combustion of these gasses creates more energy and results in a self-sustaining reaction, where no external heat source is needed. The spreading of flames can be regarded as the constant ignition of new areas caused by the heat release. The surface of the wood degrades into charcoal forming a layer between the wood and air, below which pyrolysis occurs. The rate, at which the inner layers of wood are pyrolysed is called the charring rate and lies between 0.5 and 1.0 mm/ min.

*Carbonisation or charcoal phase:* After the process has exhausted itself and the degassing has decreased, the flames die and the energy release slows down to a point where the reaction is no longer self-sustaining. At this point the reaction of the cellulose with the air/oxygen creates a glowing and smouldering effect and the temperature is too low for complete combustion and free radicals, carbon dioxide and –monoxide, water and carboxyl groups etc. are released. Depending on the biofuel this smouldering effect can be sustained for long periods of time.

Figures 1 and 2 show the two main reaction paths of combustion. With sufficient heat the biomass is mostly pyrolysed forming tar that decomposes into flammable gases. The second pathway in Figures 1 and 2 represents the thermal degradation at lower temperatures, also called the char forming pathway. Cellulose is transformed into unstable, active cellulose that decomposes and release products like carbon monoxide, carbon dioxide, free radicals and water. The insufficient heat does not ignite these gases and no visible flame can be seen (Hakkarainen *et al*. 2005).

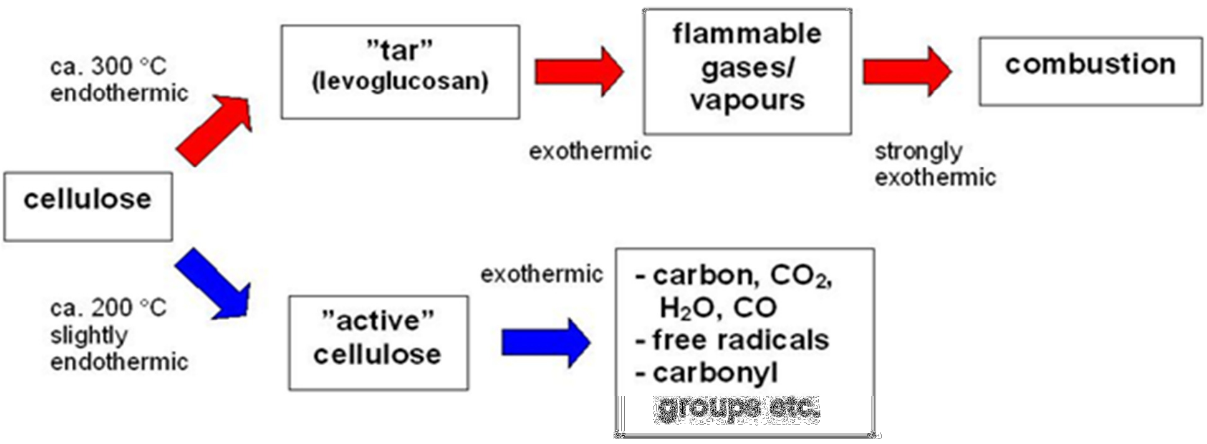


Figure 1: Combustion pathways of cellulose.

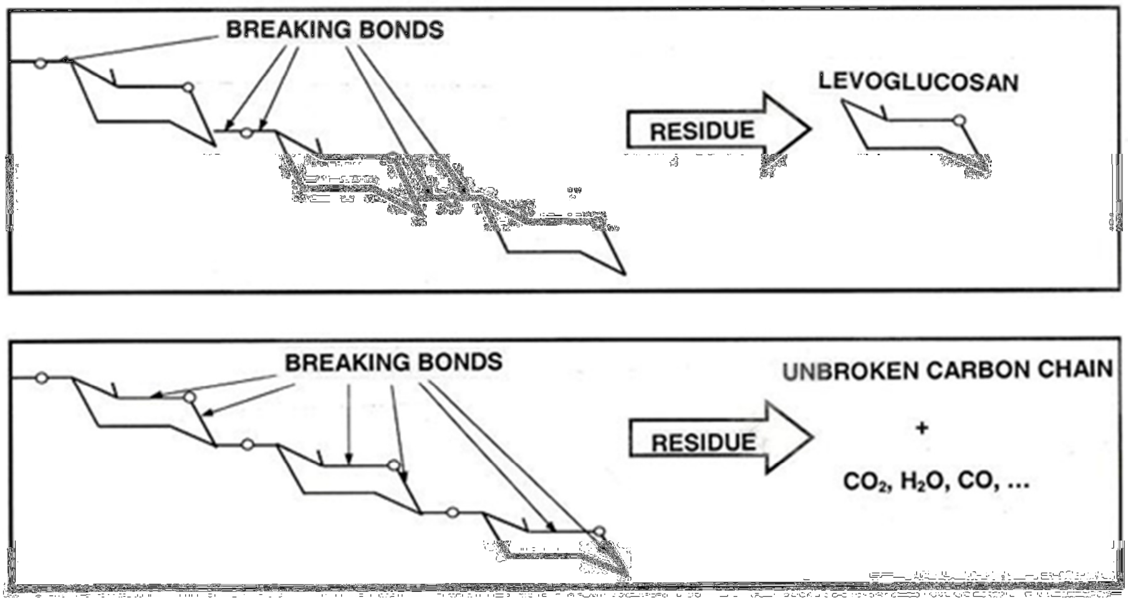


Figure 2: The two main reaction pathways of thermal decomposition of cellulose.

In all these process steps the control of air/oxygen supply to the combustion area remains the most important factor in order to control the reaction compounds that are formed. Too little oxygen into the reactor leads to incomplete combustion and the formation of hydrocarbons, carbon monoxide and carbon particulates, which further lower the temperature to below what is needed to ignite the volatile components. Too much oxygen causes the formation of toxic nitrogen oxides, sulphur dioxide and some iron oxides (Bowyer *et al.* 2003).

$$2CH_4 + xO_2 + N_2 \rightarrow CO_2 + 4H_2O + CO + 2NOx + heat$$

It is therefore important to control the burn rate, i.e. the air/oxygen supply of the reaction as it will cause efficient combustion as well as avoid unnecessary heat loss. Figure 3 shows this efficiency zone and the balance between incomplete combustion and excess heat and air loss.

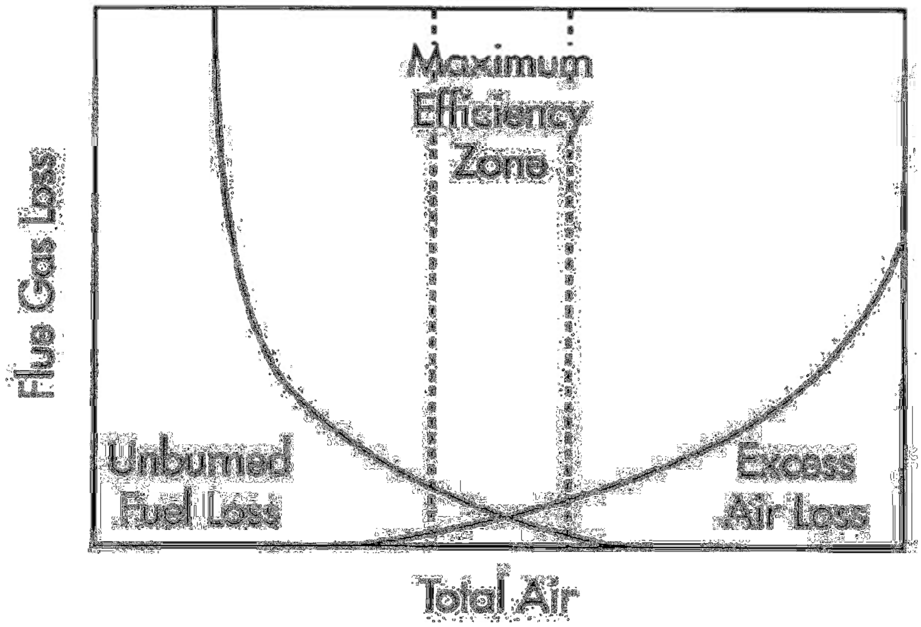


Figure 3: The maximum efficiency zone depending on the airflow

Visible smoke released from the burning area is mostly the result of incomplete combustion of carbon containing particles (soot). This is normally seen in the early stages of wood combustion and clears up as the fire burns more efficiently, allowing the smoke particles to combust and break apart. Figure 4 shows the interaction between the different phases of combustion and how the process remains self sustaining.

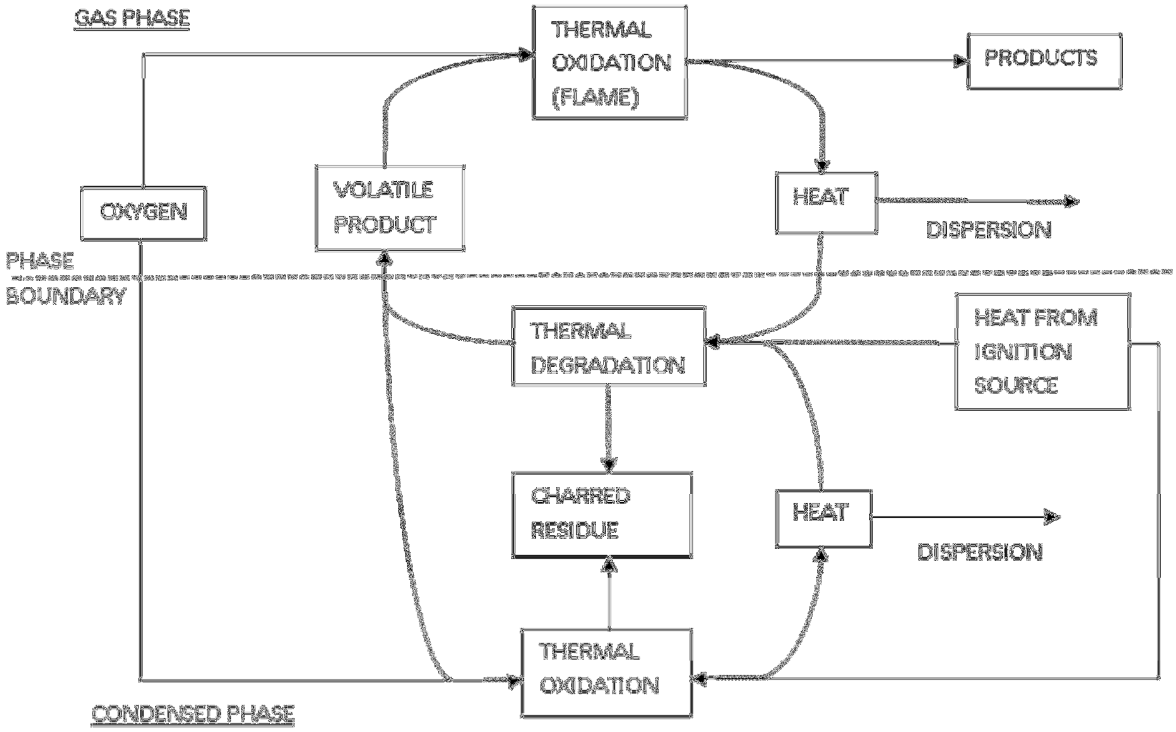


Figure 4: Schematic of polymer combustion (Camino et al. 1991)

The thermal degradation of the fuel source is initially caused by heat from the ignition source but is later replaced with heat from the thermal oxidation of the volatile products. On the other side the same thermal degradation leaves behind charred residue, which in itself undergoes thermal oxidation releasing heat and volatile products.

## 3.1 Oven design

Various small and portable oven/boiler products have been designed over the years making use of the heat released from biomass combustion. The uses of these products range from water heating to cooking stoves. Some make use of processed biomass pellets and have complex feeding and ignition systems and other, simple systems work with twigs and other forms of biomass and manual ignition.

The design for the oven used in this project was loosely based on some of these simpler products. Examples are the Rocket stove, the Karve gasifier and the Philips fan stove (Macarty *et al*. 2008) and the Kelly kettle (Anon, 2010). Most of them are light, portable and easy to clean and they contain the fire in a combustion compartment elevated from the ground by four legs. They are typically made from durable steel and contain a chimney above the fire through which exhaust gas can escape. These products are mostly made for cooking or are surrounded by a water jacket in order to heat water.

This project required only an oven with a compartment, in which a standard amount of biomass could be combusted, in order to measure temperature as a function of time and some flue gas components. The design was therefore kept as simple as possible and is displayed in Figure 5 and photograph of the final setup in Figure 6.

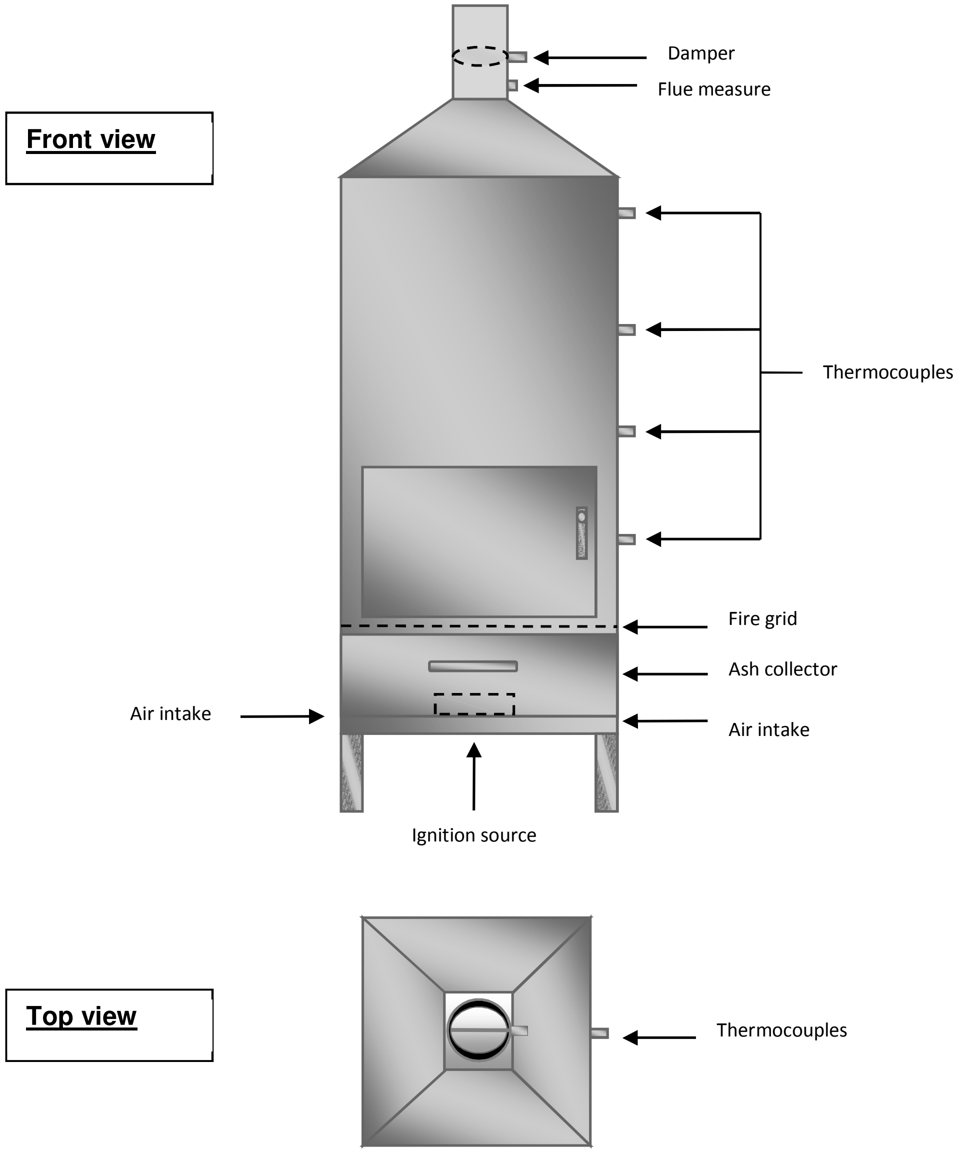


Figure 5:Schematic diagram of the front and top view of the combustion oven designed for this project.

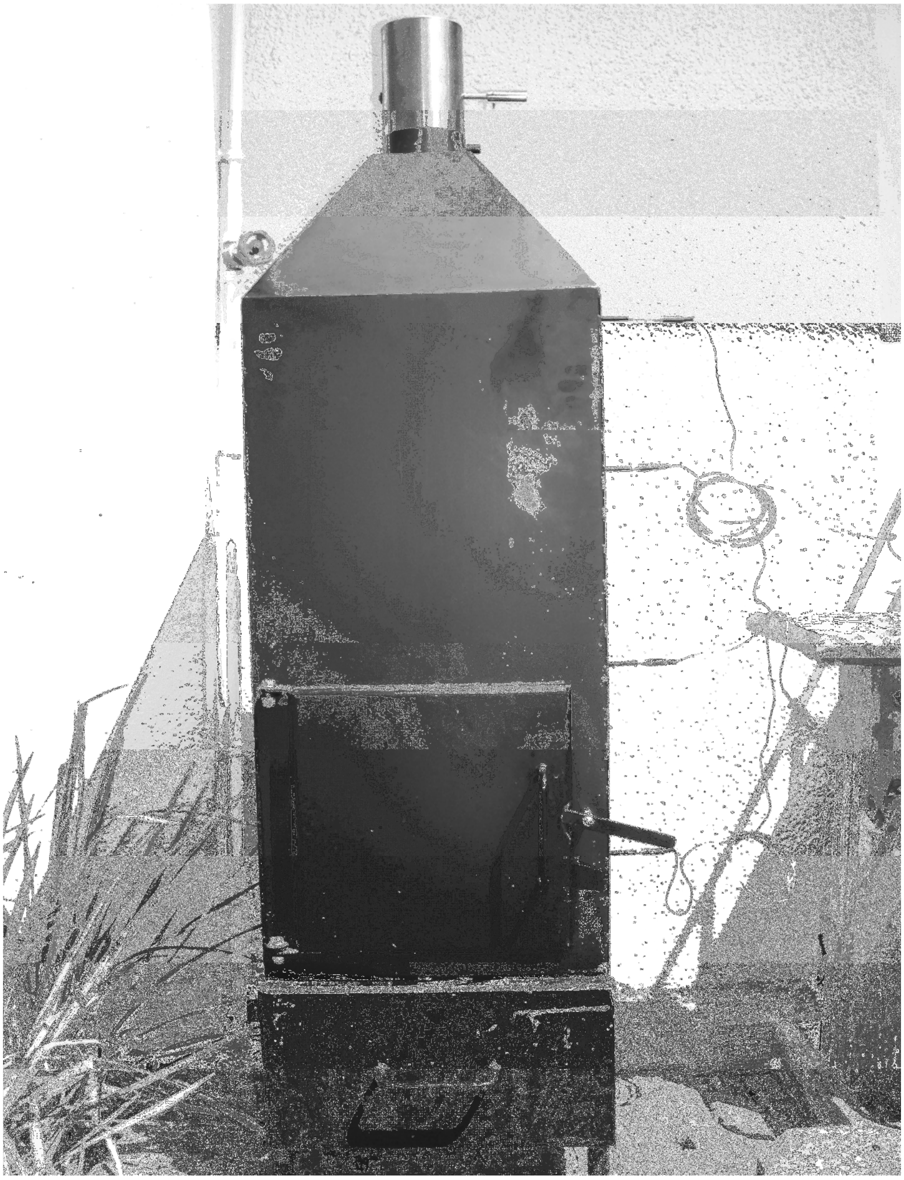

Figure 6: Combustion oven with inserted thermocouples

## 3.2 Temperature recording

The temperature was recorded at four positions above the combustion zone in order to measure the temperature at different heights. Thermocouples were inserted 150, 500, 750 and 950 mm above the base of the fire. The data was measured using a Testo 177-T4 temperature data logger. The temperature was logged in four channels, with channel

1 being the closest to the base of the fire and channel 4 being the highest above the base.

Four external K-type thermocouples working in a temperature range from -200°C to +1000°C with an accuracy of 0.5% between 70°C and 1000°C were connected to the temperature data logger. The temperatures were recorded every three seconds for the duration of the test and saved in the data logger which can record 48000 readings. After the experiment the data was downloaded to a PC and processed in MS Excel.


Figure 7: Testo 177-T4 data logger

### 3.3 Airflow

The oven has a natural airflow from openings at the bottom through the chimney and the air speed is controlled by manipulating the size of the chimney outlet by opening or closing the damper. The temperature differences cause the airflow to differ for the different combustion phases. Typically calculations take all the above factors into account, but they were developed for furnaces with a constant feed system maintaining a certain temperature and are not accurate for small scale setups, which are much more sensitive to temperature changes. In this project the flow rate was not determined but the efficiency of the airflow was estimated via the $CO_2/O_2$ ratio in the flue gas. This gives an indication of how complete the combustion is.

The oven had eight air inlets (four on two opposing sides), each with a diameter of 20 mm. The chimney had a diameter of 100 mm with a damper inside in order to be able to control the airflow through the chimney and with that directly control the combustion rate. It was found that the best preliminary results were obtained when the damper was fully open. Even a marginal reduction in the chimney airflow created large amounts of CO, which is a clear indicator of incomplete combustion.

The flue gas components were analysed using a Testo 327 flue gas analyser (Figure 8). It determines all basic functions, such as combustion efficiency, flue gas loss, $O_2$, $CO_2$, CO and flue draught. The probe is inserted into the chimney (Figure 9) and extracts the flue gas, which is passed through a particle filter and is analyzed by chemical measuring cells. The following data is displayed after one measurement and saved to one of 20 memory spots


Figure 8: Testo flue gas analyzer

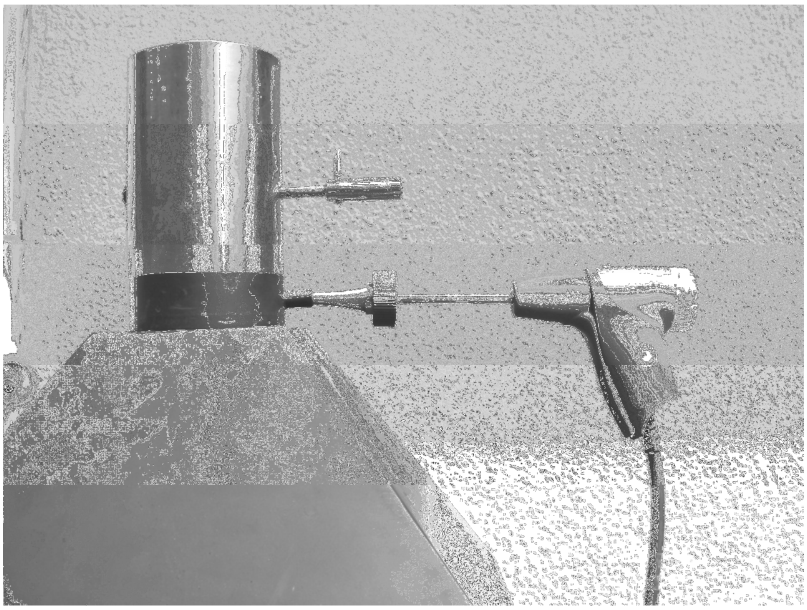

Figure 9: Flue gas extraction probe

- Temperature measurement:

| | |
|---|---|
| Measuring range: | -40 to +600 °C |
| Accuracy: | ±0.5 °C (0 to +99,9 °C) |
| | ±0.5 % of m.v. (from +100°C) |

- Determination of combustion efficiency (ETA)

| | |
|---|---|
| Measuring range: | 0 to 120 % |
| Resolution: | 0.1 % |

- Exhaust loss:

| | |
|---|---|
| Measuring range: | 0 to 99.9 % |
| Resolution: | 0.1 % |

- $O_2$ content:

| | |
|---|---|
| Measuring range: | 0 to 21 Vol.% |
| Accuracy: | ±0.2 Vol.% |
| Resolution: | 0.1 % |

- $CO_2$ content:

| | |
|---|---|
| Display range: | 0 to CO2max |
| Accuracy: | ±0.2 Vol.% |
| Resolution: | 0.01 Vol.% |

- CO content:

| | |
|---|---|
| Measuring range: | 0 to 4000 ppm |
| Accuracy: | ±20 ppm (up to 400 ppm) |
| | ±5 % of m.v. (up to 1000 ppm) |
| | ±10 % of m.v. (up to 4000 ppm) |
| Resolution: | 1 ppm |

## 3.4 Sample collection and preparation

Samples were divided into two groups: fire wood commonly sold in the Western Cape and charcoal products. To ensure a better representation of these products, they were obtained from three different locations or brands. The only exception were pellets, wood bricks as these products are less common and only one brand was available. Purchases were made at shopping centres, petrol stations and street vendors. For each product or species the three samples were combined into one representative sample.

Blocks of the size 15 x 4 x 2 cm containing both heart- and sapwood were cut from the fire logs to obtain a uniform size for all samples. These dimensions were determined by experimentation with different sizes. Smaller blocks burnt too quickly and did not provide a meaningful burning profile. Larger blocks burnt too long and required a longer exposure to the ignition source, which affected the combustion profile

The other products like the charcoal, briquettes and pellets remained in their original size.

Before each test the samples were oven dried at 103$^{o}$C for at least 24 hours.

## 3.5 Combustion parameters

Before the actual experiments several tests were conducted with pine wood in order to determine the optimal type and amount of ignition fuel as well as the optimum ratio of wood / fuel. It was determined that the slightest restriction in the airflow with the damper in the chimney caused a loss of oxygen and smothered the flames, inhibiting complete combustion. It was also found that ignition improved with a small, approximately half a centimetre gap between the individual wood blocks in order to allow flames and air to reach into the wood stack. This allowed for even burning throughout the stack.

Methylated spirit and firelighters, commonly known as Blitz were tested as ignition fuel. The spirit showed a much better time/temperature profile, as displayed in Figure 10. It had a short but very hot temperature peak in the beginning and the flame remained relatively large until nearly everything was burnt, whereas the blitz took longer to ignite and the flame died slowly after reaching its peak temperature, which makes it difficult to identify the ignition source in the temperature profile and separate it from the biofuel.

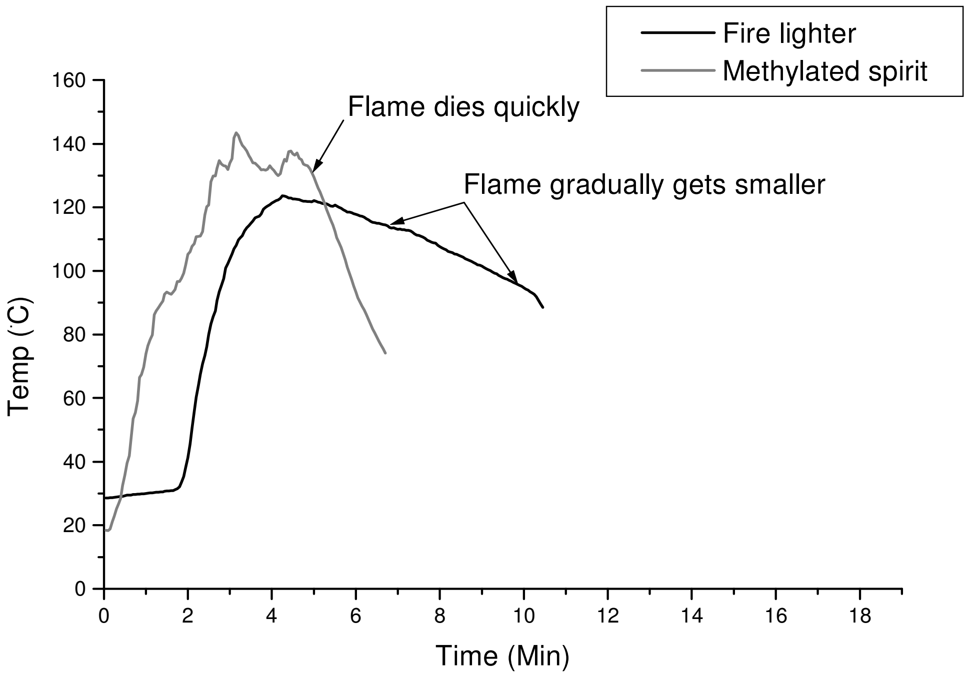


Figure 10: Time/ Temperature profile of methylated spirits and solid fuel fire lighters (Blitz).

Finally an amount of 40ml methylated spirit was chosen as ignition source for further experiments, because this was sufficient to ignite even the denser wood species, such as Camelthorn, as well as the charcoal products. This amount is also not too much, which would extend its burn time into that of the wood combustion and interfere with the temperature profile of the biomass. The spirit was 180 mm below the wood fuel and in a 100 ml container. Table 2 shows the burning times for methylated spirit.

| Methylated spirit [ml] | Burn time [min] |
|---|---|
| 10 | 02:24 |
| 20 | 03:17 |
| 40 | 04:47 |
| 40 | 05:42 |
| 50 | 06:46 |
| 60 | 07:50 |

Table 2: Burning times for methylated spirit.

Subsequently several tests were conducted with different combinations of wood weight, block size, container diameter, and amount of metylated spirit as well as the spacing between the wood blocks within the stack. Pine was used as fuel for all preliminary tests as it was readily available and was easy to cut to exact sizes. Table 3 shows the results of the different tested combinations.

| Biomass | Sample Weight | Methylated spirit | Container diameter | Blocks | Stacking |
|---|---|---|---|---|---|
| Pine | 1kg | 135ml | 65mm | 15mmx15mmx15cm | no gaps |
| Pine | 1kg | 50ml | 65mm | 15mmx15mmx15cm | no gaps |
| Pine | 1kg | 50ml | 100mm | 15mmx15mmx15cm | no gaps |
| Pine | 1kg | 60ml | 100mm | 15mmx15mmx15cm | 5-10mm spacing |
| Pine | 1kg | 40ml | 100mm | 15mmx15mmx15cm | 5-10mm spacing |
| Pine | 1.5kg | 30ml | 100mm | 20mmx40mmx15cm | 5-10mm spacing |
| Pine | 1.5kg | 40ml | 100mm | 20mmx40mmx15cm | 5-10mm spacing |
| Camelthorn | 2.5kg | 40ml | 100mm | 20mmx40mmx15cm | 5-10mm spacing |

Table 3: Determination of optimal fuel/ignition amounts

These tests revealed that 1.5 kg of biomass would be the optimum standard weight for each of the combustion tests. This was enough to obtain a combustion profile with distinguishable details, without burning for an unnecessary long time. For all tested products the same mass was combusted to allow comparison of the profiles.

The optimum size of the blocks was determined to be 150mm length, 40mm width and 20mm height. Smaller blocks burnt too rapidly and did not form proper coal after the flames died out. Larger blocks burnt too long and were difficult to cut as there were very few fire logs per bag that were thick enough, especially from the vine stumps. Figure 11 shows a quatity of 1.5 kg Black Wattle with all the blocks cut as close as possible to size.

Figure 11: 1.5kg Black Wattle blocks

# 4. Results and Discussion

## 4.1 Preliminary tests

Figure 12 shows the results of the preliminary tests conducted with 1.5 kg pine wood ignited with 40 ml methalyted spirit. It shows the time/temperature profiles recorded at the four different height positions above the base of the fire.

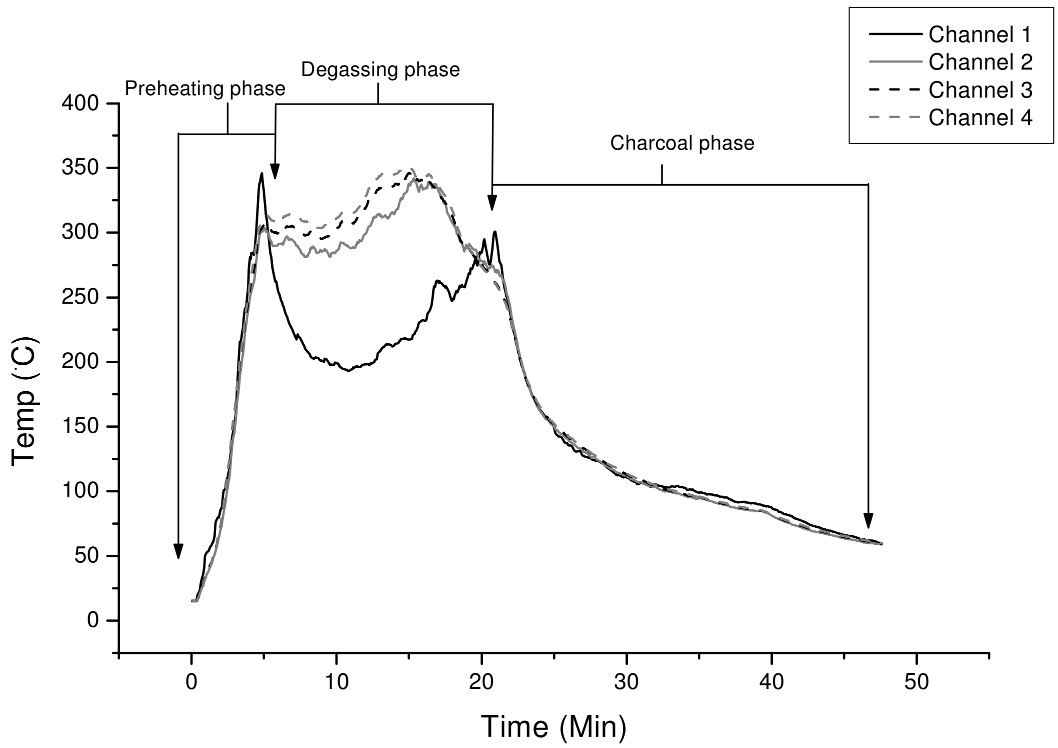


Figure 12: Combustion profiles at four different height positions of 1.5kg pine ignited with 40ml methalyted spirit.

The profiles for channel 2, 3 and 4 showed a similar trend, but the profile closest to the fire (channel 1) did not follow the same curve. For this reason channel 1 and 3 were chosen for all further presentations to compare the different biofuels, as channel 1 shows a unique profile and channel 3 is representative of all the profiles sufficiently high above the fire base.

The different profile determined in channel 1 can be explained by the fact that the temperature sensor is located within the fire, whereas the other probes record the radiated heat rising from the fire below.

The quick rise in temperature, as well as the first peak around 4 minutes can be attributed to the ignition of the methalyted spirit. After this point the ignition flame dies and a slight drop in temperature can be observed. This is the preheating phase.

Subsequently, the biomass starts to burn in the degassing phase. At the second peak the biomass reaches its maximum combustion temperature, which is followed by a decrease in temperature after about 25 – 30 min as the flames are dying out. This is the charcoal phase, which is marked by a steady decline in temperature. All these are indicated in Figure 12

## 4.2 Biofuel comparison

### 4.2.1 Channel 1 Time/Temperature profiles

The figures below show the comparative results for the channel 1 temperature recording from the combustion tests conducted for the various biomass fuels. These represent the temperature recorded in the fire over a period of time. The time/temperature profiles are divided into three graphs, Figure 13, 14 and 15, for easier reading. Figure 13 and 14 contain the profiles for all the wood species as well as the wood based products namely the wood- briquettes and pellets, respectively. Figure 15 contains the profile for the three tested coal products.

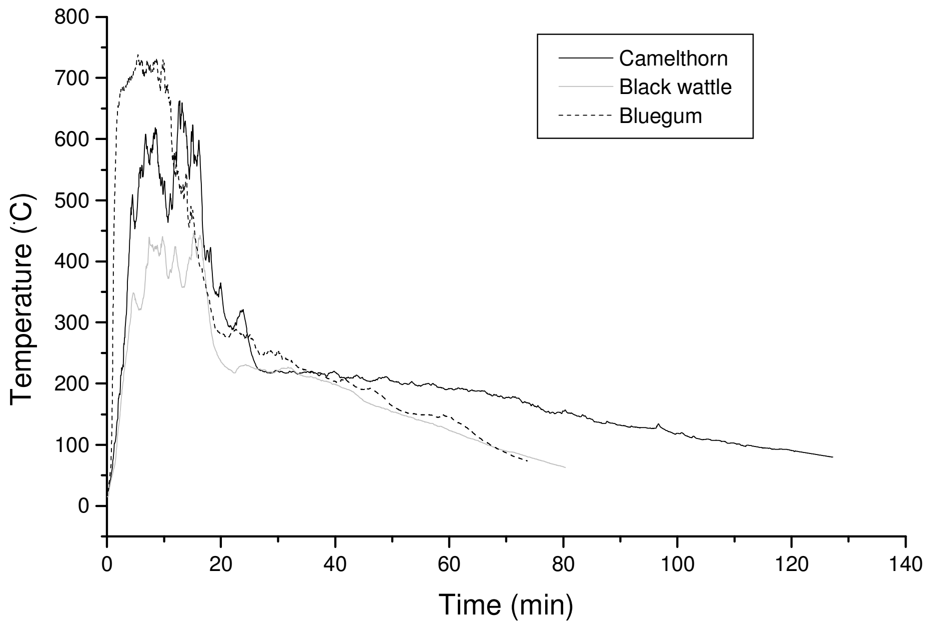


Figure 13: Time/temperature profile in the fire of Camelthorn, Black Wattle and Bluegum

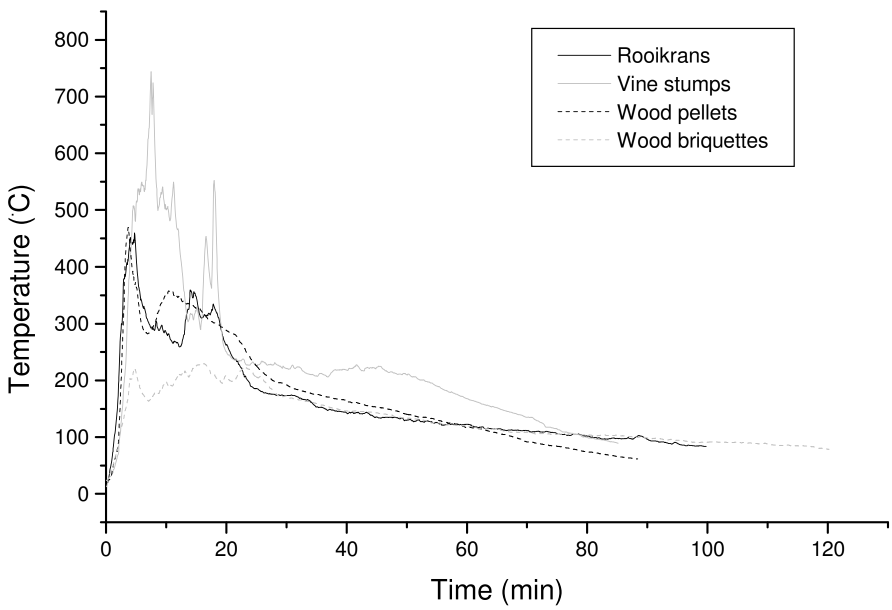


Figure 14: Time/temperature profile in the fire of Rooikrans, wood pellets, vine stumps and wood briquettes

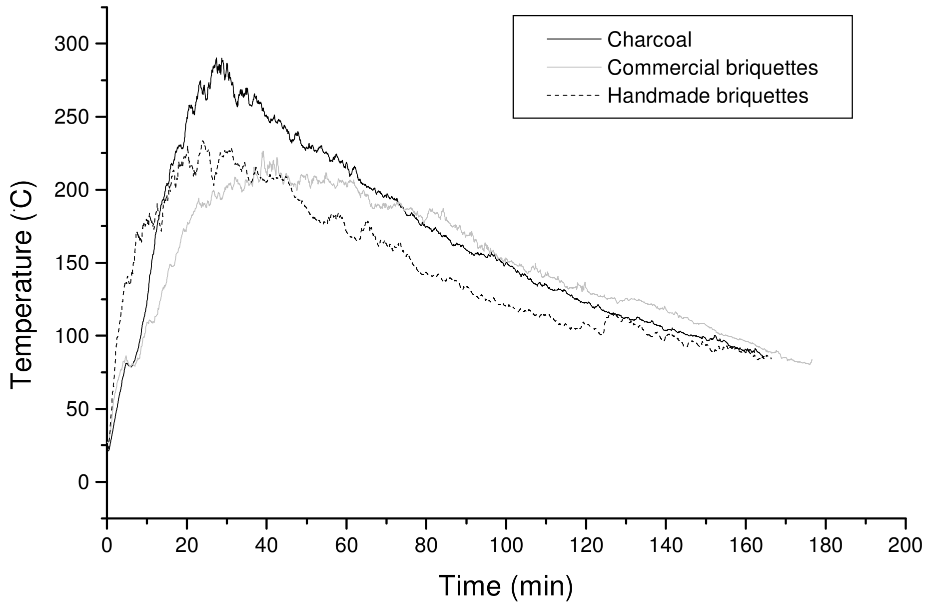


Figure 15: Time/temperature profile in the fire of commercial briquettes, charcoal and handmade briquettes.

Table 4 shows characteristic values derived from the time/temperature profiles, such as the maximum temperature ($T_{max}$,), the time required to reach it (t to $T_{max}$) the coal temperature ($T_{coal}$) the time required to reach it (t to $T_{coal}$), how long it took until it decreased below 80°C ( t $T_{coal}$ to 80°C) and how fast this decrease happened (Coal decline).

The temperature where the graph started to become smoother after it had reached its maximum temperature was regarded as $T_{coal}$.

The decline to 80°C was chosen because this temperature is considered to be too low to be an effective heat source (e.g. for cooking) and leaves enough time in the graph to determine the decline rate from the point of coal formation.

| | $T_{max}$ (˚C) | $T_{coal}$ (˚C) | t to $T_{max}$ (min) | t to $T_{coal}$ (min) | t $T_{coal}$ to 80°C (min) | Coal decline (˚C/min) |
|---|---|---|---|---|---|---|
| Camelthorn | 662.28 | 219.88 | 12.72 | 27.82 | 126.95 | 1.41 |
| Black Wattle | 443.35 | 227.44 | 15.15 | 23.87 | 74.38 | 2.92 |
| Bluegum | 738.96 | 283.94 | 5.46 | 22.25 | 71.4 | 4.15 |
| Rooikrans | 358.92 | 183.41 | 14.07 | 24.93 | 100.44 | 1.37 |
| Vine stumps | 744.77 | 238.96 | 7.69 | 20.81 | 88.62 | 2.37 |
| Wood pellets | 358.31 | 196.76 | 10.55 | 28.15 | 77.06 | 2.34 |
| Wood briquettes | 232.01 | 173.79 | 16.38 | 29.5 | 118.49 | 1.05 |
| Commercial charcoal | 290.32 | 206.39 | 27.3 | 63.26 | 167.75 | 1.21 |
| Commercial briquettes | 226.75 | 186.25 | 39.06 | 81.13 | 177.88 | 1.10 |
| Handmade briquettes | 234.23 | 180.01 | 23.82 | 51.97 | 174.09 | 0.82 |

Table 4: Comparison of characteristic values acquired from the channel 1 time/temperature profiles.

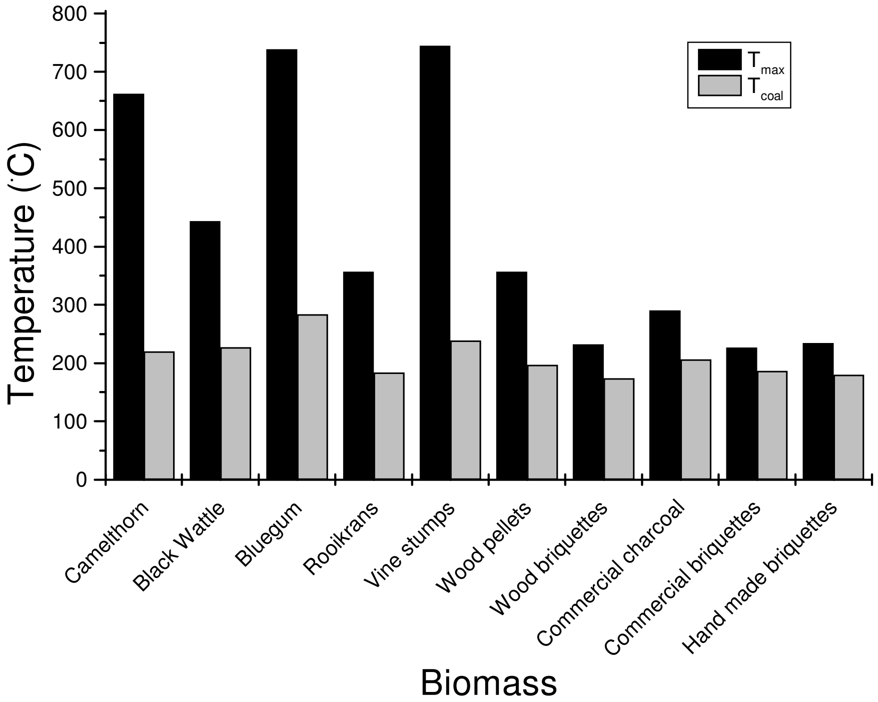


Figure 16: Temperature comparison of the maximum temperature ($T_{max}$) and the coal temperature ($T_{coal}$) for channel 1 time/temperature profiles

Vine stumps reached with 744.77˚C the highest temperature. The different and rather erratic temperature profile measured in channel 1 can be explained by the quick release of volatile gasses trapped within the wood structure; such pockets were observed when the samples were prepared. Vine stumps also have a relatively low density of about $500kg/m^3$, which contributes to the high ignition and combustion rate. Bluegum reached a similar high temperature of 738.96˚C, which can be attributed to the presence of highly flammable oils increasing the combustion rate. In both cases they had reached these maximum values faster than any other biofuel - in 7.69 min and 5.46 min, respectively. The third highest value of 662.28˚C was reached by Camelthorn after 12.72min. Black Wattle and Rooikrans reached 443.35˚C and 358.92˚C after 15.15 min and 14.07 min, respectively.

All the processed biomass reached higher temperatures than the unprocessed products and required a longer time (apart from the wood pellets) to reach the maximum temperature: wood pellets reached 358.31˚C in 10.55 min, commercial charcoal reached 290.32˚C in 27.3 min, handmade briquettes reached 234.23˚C in 23.82 min, wood briquettes reached 232.01˚C in 16.38 min and the commercial coal briquettes reached 226.75˚C in 39.06 min.

Bluegum and Vine stumps also had the highest coal temperature ($T_{coal}$) of 283.94˚C and 238.96˚C, respectively, followed by Black Wattle (227.44˚C), Camelthorn (219.88˚C) and commercial charcoal (206.39˚C). The lowest coal temperatures were observed from wood pellets (196.76˚C), commercial briquettes (186.25˚C), Rooikrans (183.41˚C), handmade briquettes (180.01˚C) and finally the wood briquettes (173.79˚C).

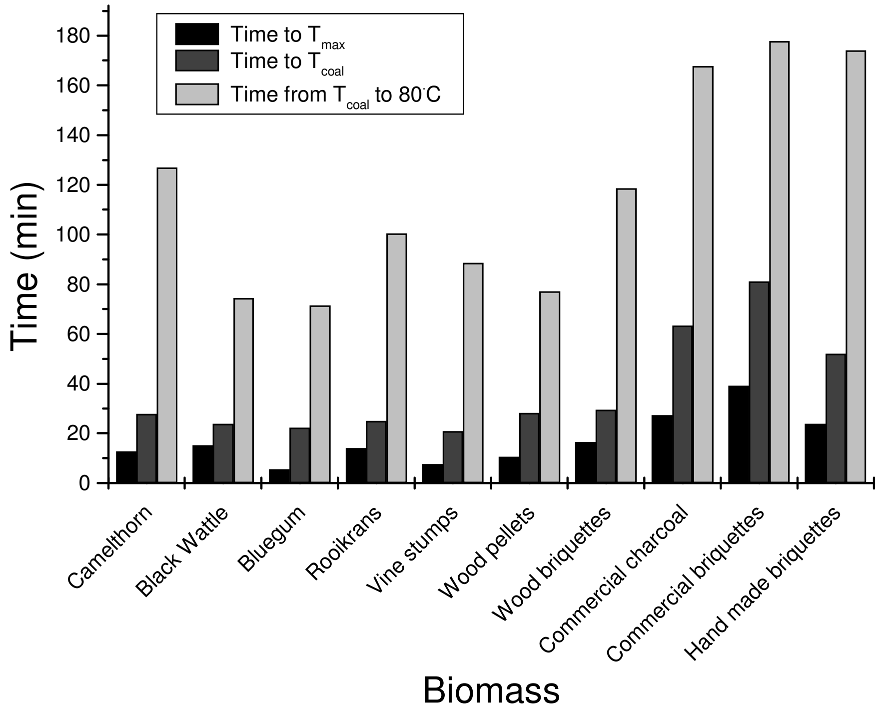


Figure 17: Comparison of time required to reach $T_{max}$, time until flame dies out ($T_{coal}$) and time from $T_{coal}$ to 80˚C for channel 1 time/temperature profiles

Vine stumps and Bluegum were the first to reach their maximum temperatures and their coal temperature with 20.81 min and 22.25min. At this point the flames die out and heat is released by smouldering coals (charcoal phase). Black Wattle and Rooikrans followed with t to $T_{coal}$ of 23.87min and 24.94min. Camelthorn took the longest to reach $T_{coal}$ after 27.82min, due to its high density of 963 kg/$m^3$.
The processed wood products required a long time to reach $T_{coal}$, much like the denser wood species, due to the fact that these products densified - the pellets have a typical density of 650 kg/$m^3$ (Kofman 2007) and wood briquettes up to 1200 kg/$m^3$ (Grover and Mishra 1996). Their coal forming times extended up to 28.15 min for the pellets and 29.5 min for the wood briquettes.

Charcoal performed different altogether. They required more time to reach $T_{max}$ due to the fact that they don't combust as normal wood would, and do not undergo a degassing phase. At some point during the maximum temperatures flames were visible indicated by the sharp temperature changes between 20 and 60 min (Figure 15). After this point the profiles tended to smooth out in a steady temperature decline, which was significantly slower than for any wood species. Handmade briquettes reached $T_{coal}$ after 51.63 min, charcoal after 63.26 min and the commercial briquettes after 81.13 min.

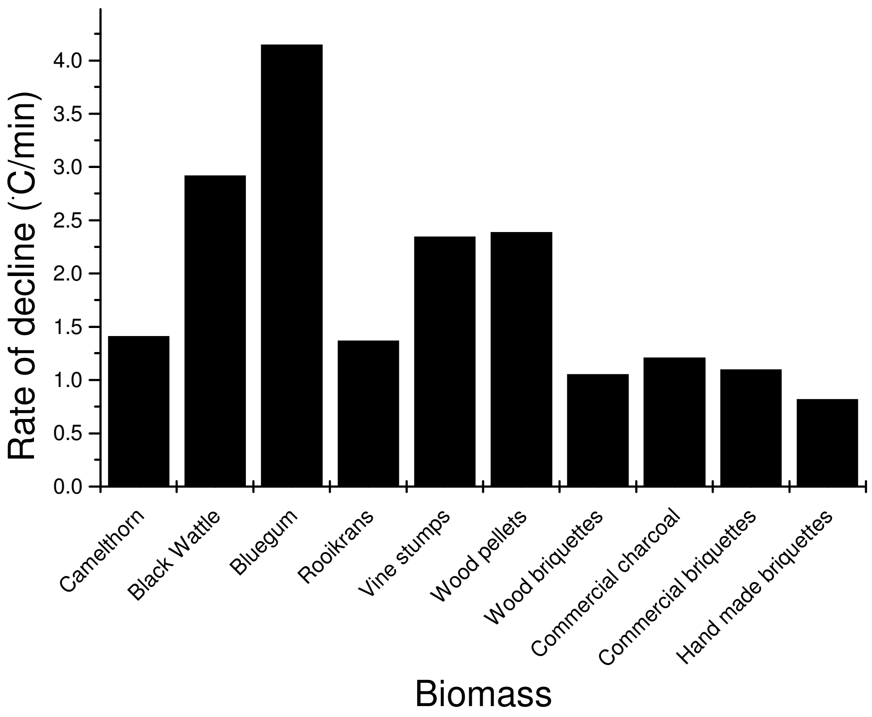


Figure 18: Coal temperature decline rate measured through channel 1.

Of large interest is the rate of temperature decline from the point when the flames die out ($T_{coal}$) to 80˚C. The handmade briquettes showed a very low temperature decline of 0.82˚C/min, caused by added fire retardant (soil). The wood briquettes followed with 1.05˚C/min and the commercial coal briquettes with 1.10˚C/min. Charcoal had a temperature decline of 1.21˚C/min. The acacias also had a low temperature decline: Rooikrans and Camelthorn achieved 1.37˚C/min and 1.41˚C/min, respectively followed by vine stumps (2.34˚C/min), wood pellets (2.39˚C/min), Black Wattle (2.92˚C/min) and lastly (known to be a bad “braai” wood) Bluegum, which lost temperature with 4.15˚C/min at almost double the rate of the other biofuels.

A general trend was that a higher the coal temperature ($T_{coal}$) led to a faster temperature decline. A linear fit yielded an $R^2$ value of 0.784which means that the $T_{coal}$ decline can be predicted with a 78.4% accuracy with a linear model. The fitting function was
y = -3.90061+ 0.02754x.

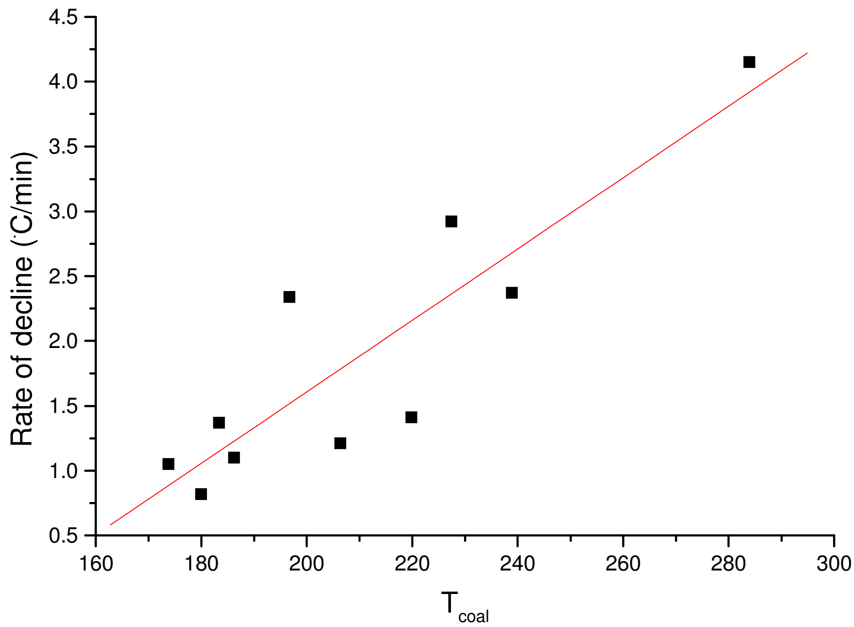


Figure 19: Linear regression for the temperature decline as a function of $T_{coal}$

### 4.2.2 Channel 3 Time/Temperature profiles

Figures 20, 21 and 22 represent the temperature profiles recorded for the various biofuels from channel 3 located about 65 cm above the base of the fire. Table 5 shows the same characteristic values as table 4, acquired from these temperature profiles.

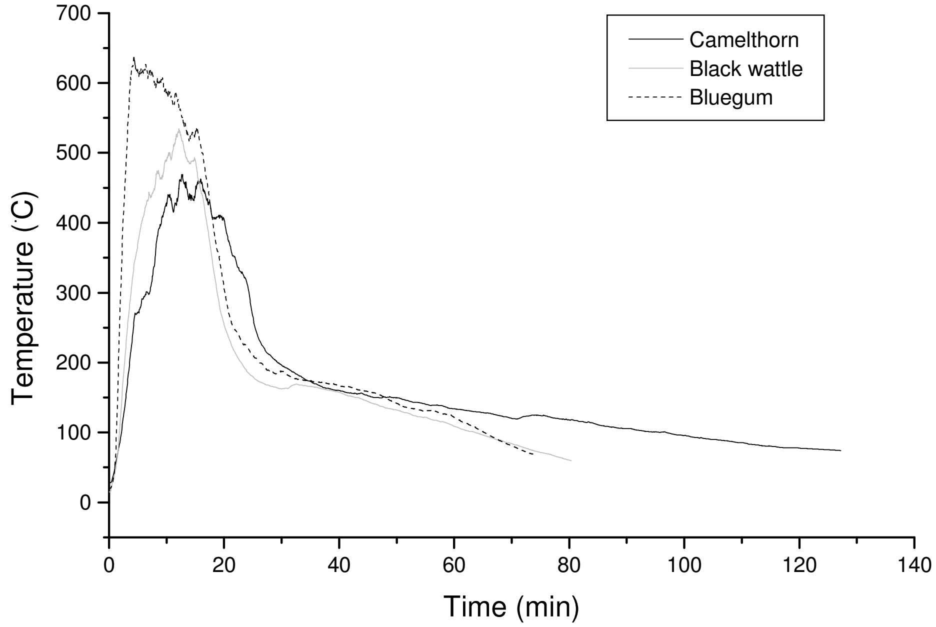


Figure 20: Channel 3 time/temperature profile for Camelthorn, Black Wattle and Bluegum

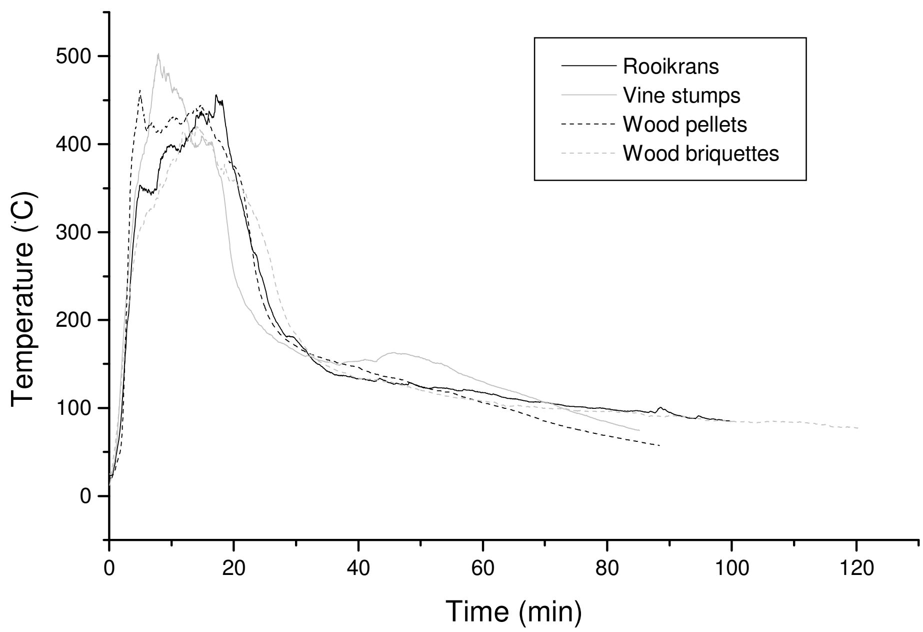


Figure 21: Channel 3 time/temperature profile for Rooikrans, wood pellets, vine stumps and wood briquettes

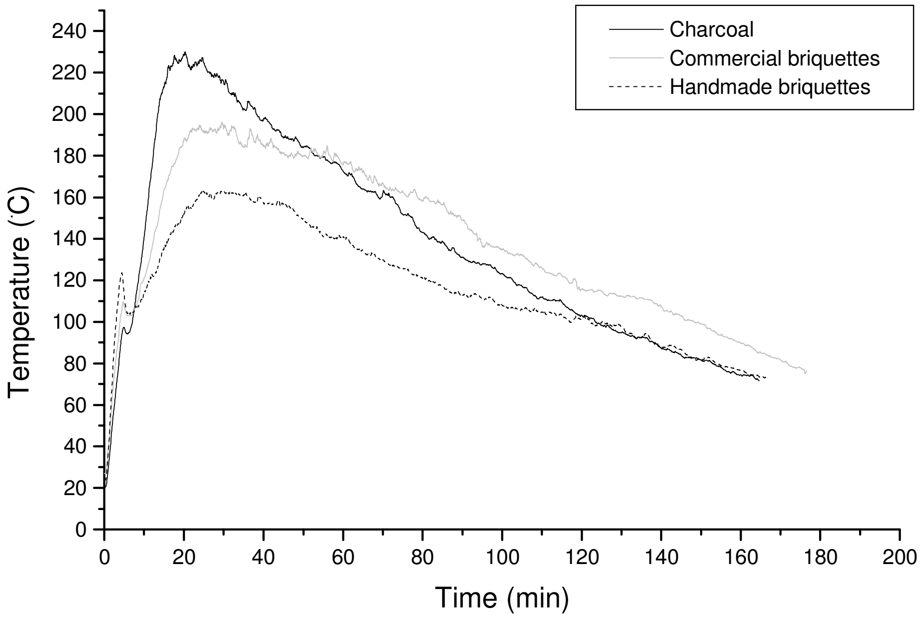


Figure 22: Channel 3 time/temperature profile for store bought briquettes, charcoal and handmade briquettes

| | $T_{max}$ (˚C) | $T_{coal}$ (˚C) | t to $T_{max}$ (min) | t to $T_{coal}$ (min) | t $T_{coal}$ to 80°C (min) | Coal decline (˚C/min) |
|---|---|---|---|---|---|---|
| Camelthorn | 469.43 | 176.55 | 12.99 | 33.83 | 114.39 | 1.20 |
| Black Wattle | 533.08 | 165.87 | 12.12 | 28.91 | 70.92 | 2.04 |
| Bluegum | 627.44 | 189.91 | 6.38 | 27.39 | 69.72 | 2.60 |
| Rooikrans | 455.99 | 144.78 | 17.29 | 34.83 | 104.61 | 0.93 |
| Vine stumps | 402.64 | 162.94 | 7.84 | 31.32 | 81.89 | 1.64 |
| Wood pellets | 445.31 | 173.97 | 14.88 | 29.06 | 71.65 | 2.21 |
| Wood briquettes | 420.39 | 144.78 | 14.08 | 35.29 | 114.72 | 0.82 |
| Commercial charcoal | 230.27 | 164.39 | 20.26 | 64.66 | 152.28 | 0.96 |
| Commercial briquettes | 195.99 | 158.16 | 29.47 | 82.06 | 80.71 | 0.83 |
| Handmade briquettes | 163.5 | 141.39 | 24.98 | 55.29 | 154.36 | 0.62 |

Table 5: Comparison of characteristic values acquired from the channel 3 time/temperature profiles.

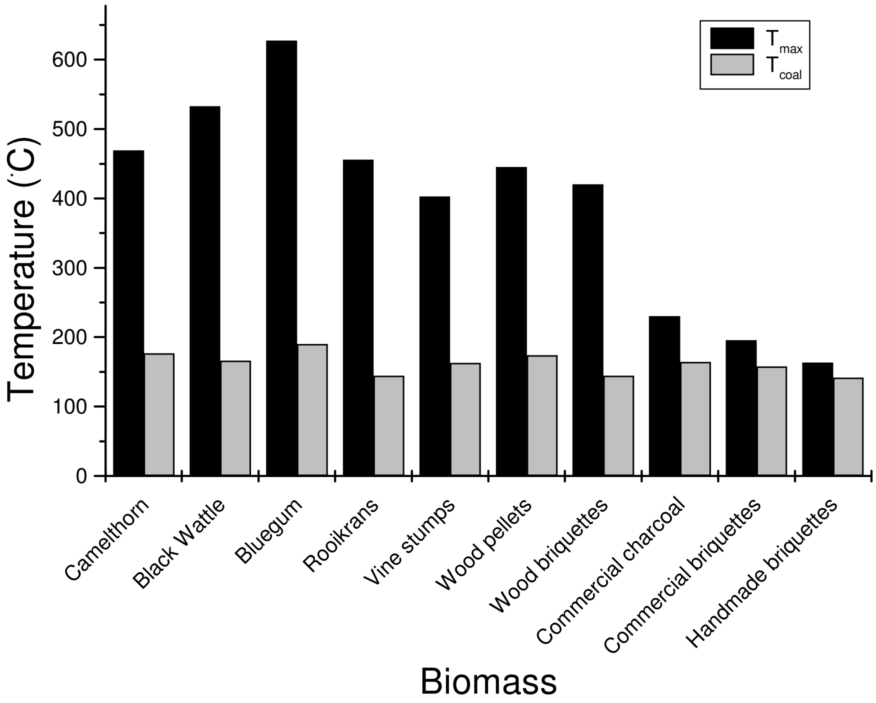


Figure 23: Temperature comparison of the maximum temperature ($T_{max}$) and the coal temperature ($T_{coal}$) for channel 3 time/temperature profiles.

At first sight $T_{max}$ does not seem to correspond well to the measurements recorded by channel 1, but apart from the vine stumps and Black Wattle the ranking of all the wood species and processed biofules agrees well with channel 1.

The highest temperature recorded at this level as indicated in Figure 23 and Table 5 was reached by Bluegum (627.44˚C), followed by Black Wattle (533.08˚C), Camelthorn (469.43$^{o}$C), Rooikrans (455.99$^{o}$C), wood pellets (445.31$^{o}$C), wood briquettes (420.39˚C), vine stumps (402.64$^{o}$C), charcoal (230.27˚C), commercial coal briquettes (195.99˚C) and finally handmade briquettes (163.5˚C).

The charcoal forming temperature, $T_{coal}$, also showed a good correlation to the channel 1 measurements, apart from the vine stumps and wood pellets. Bluegum again recorded the highest temperature of 238.94˚C, followed by vine stumps (238.96˚C), Black Wattle (227.44˚C), Camelthorn (219.88˚C), commercial charcoal (206.39˚C), wood pellets (169.76˚C), commercial briquettes (186.25˚C), Rooikrans (183.41˚C), the handmade briquettes (180.01˚C) and wood briquettes (173.79˚C).

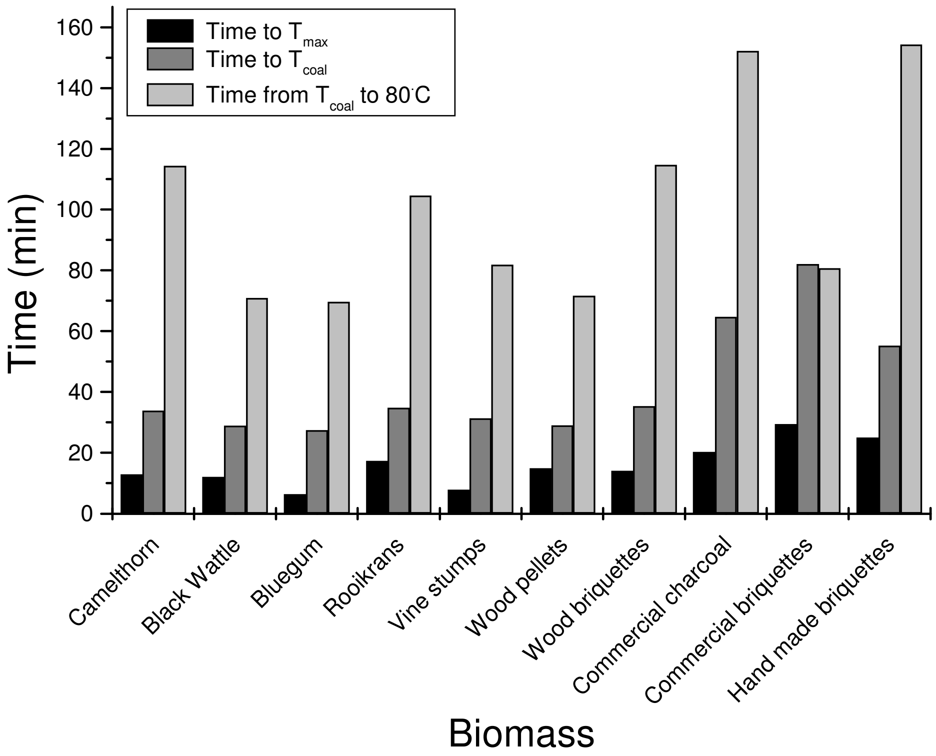


Figure 24: Comparison of time required to reach $T_{max}$, time until flame dies out ($T_{coal}$) and time from $T_{coal}$ to 80˚C for channel 3 time/temperature profiles

The times determined by channel 3 do not compare well with the recording of channel 1. This can be explained by the fact that the higher temperature probe experiences less spikes and temperature fluctuations than the probe in the fire.

Bluegum reached $T_{max}$ the fastest after 6.38 min, followed by the vine stumps (7.84 min), Black Wattle (12.12 min), Camelthorn (12.99 min), wood briquettes (14.08 min), wood pellets (14.88 min), Rooikrans (17.29 min), charcoal (20.26 min), handmade briquettes (24.98 min) and commercial charcoal (29.47 min).

The time $T_{coal}$ it took for the flames to die, which is also the end of the degassing phase are as follows: Black Wattle (28.91 min), wood pellets (29.06 min), Bluegum (27.39 min) vine stumps (31.32 min), Camelthorn (33.83 min), wood briquettes (35.29 min), handmade briquettes (55.29 min), charcoal (64.66 min) and commercial charcoal (82.06 min).

Figure 25 indicates the temperature decline from $T_{coal}$ to 80$^{o}$C measured by channel 3. Higher above the coals the rate of decline seems to be lower than that measured inside the fire. This may be due to the fact that channel 3 is affected by the radiant heat in the combustion chamber.

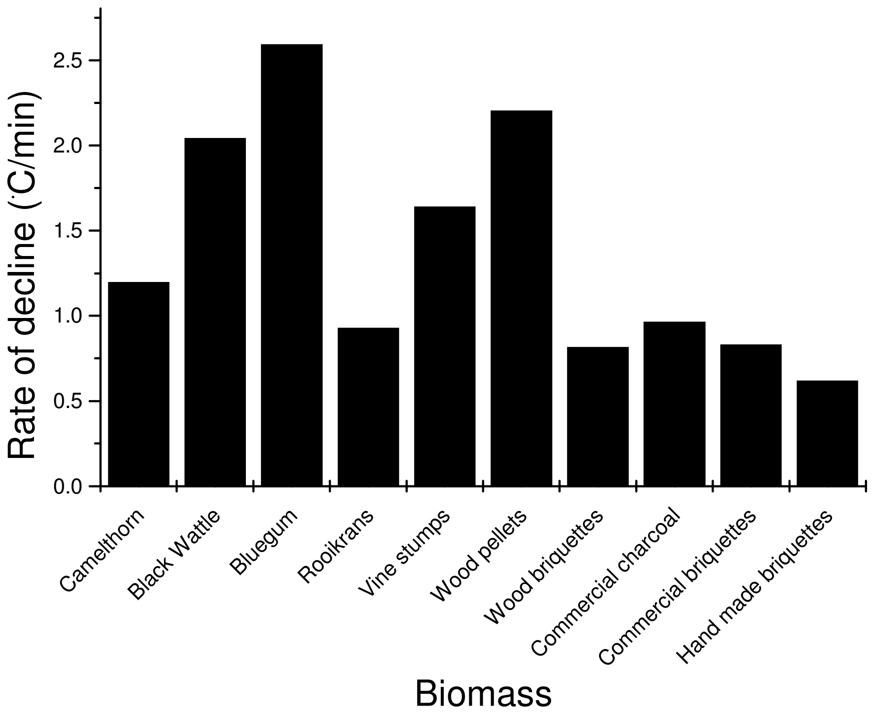


Figure 25: Coal temperature decline rate measured through channel 3

The main reason why charcoal and the coal briquettes burnt at lower temperatures and for longer times is that charcoal tends to have a much lower volatile mater content (around 30%) compared to wood (75-85%). This causes the coal products to burn less vigorously and together with a higher carbon content (50% to 95%) this leads to longer burning times (Anon 1987).

Handmade briquettes lost temperature over the longest period (0.62˚C/min), followed by wood briquettes (0.82˚C/min), commercial briquettes (0.83˚C/min), Rooikrans (0.93˚C/min), charcoal (0.96˚C/min), Camelthorn (1.20˚C/min), vine stumps (1.64˚C/min), Black Wattle (2.04˚C/min), wood pellets (2.21˚C/min) and again Bluegum had the fastest decline rate with 2.60˚C/min.

A linear fit yielded an $R^2$ value of 0.654, which means that the $T_{coal}$ decline can be predicted with 65.4% accuracy with a linear model from the $T_{coal}$ temperature as indicated in Figure 26. The fitting function was y = -3.90061+0.02754x.

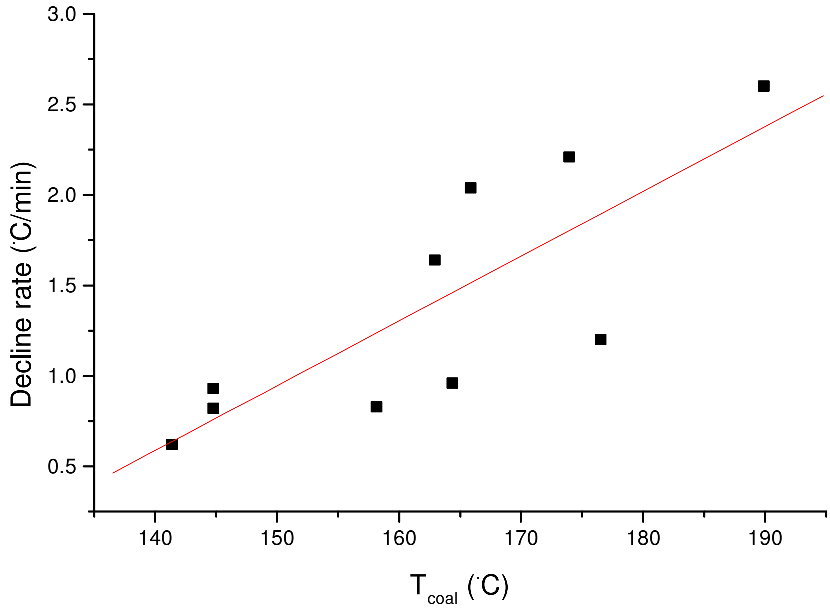


Figure 26: Linear regression for the temperature decline as a function of $T_{coal}$

The combustion characteristics of the various biofuels greatly influence its potential for its use on an industrial scale in combustion/furnace systems. Ideally they should burn fast with high temperatures, but more importantly the fuel should be homogenous in shape, moisture content, volatile matter and ash content, as this greatly affects the operation of the combustion system. Lower quality fuels, even if they achieve high combustion temperatures, would need significant pre-treatment which would inevitably increase the cost. Best suitable for industrial purposes is therefore the processed biomass, namely wood briquettes, wood pellets and coal products. From these the wood pellets performed better than wood briquettes and the charcoal would be better suited than coal briquettes.

The informal use of biofuel (e.g. for cooking) relies more on the coal temperature and decline rate, because only a limited maximum temperature is needed for a long enough time. Too hot coal temperature is also negative as it burns the food rather tan cook it.
For this purpose the Rooikrans performed best as it had the lowest temperature decline, as well as a moderate coal temperature, at which food could be prepared. Camelthorn also showed high potential, but its high coal temperature may result in waiting time for the temperature to decrease to suitable values. These findings support the popularity of these two species as braai wood in South Africa.
Coal is an ideal cooking fuel but is in most cases too expensive for poorer communities, which rather depend on self collected woody biomass from surrounding trees and shrubs for their fuel sources.

For heating purposes longer burning time and high temperatures would be desirable. In this regard the wood briquettes showed the best potential, not necessarily with the highest temperature but with the longest burning time. Apart from the wood briquettes, Rooikrans and Camelthorn also showed good properties but although the coals burned for longer they did not achieve high enough temperatures to be efficient as heating material.

## 4.3 Flue gas

Both the carbon monoxide (CO) and carbon dioxide ($CO_2$) levels showed a significant difference between woody biofuels and coal products. This can be attributed to the fact that the coal products never clearly undergo a degassing phase, in which they are heated beyond their flash point and where self sustained combustion produces flames and heat high enough to bind carbon to atmospheric oxygen to create $CO_2$. In contrast woody biomass quickly reaches its flashpoint enabling volatile gasses to oxidise and form $CO_2$.

### 4.3.1 Carbon monoxide

Figure 27 shows that all woody biomass, except Black Wattle undergo a reduction in CO from the preheating phase to the degassing phase. The low amount of CO released by Black Wattle in the first phase can probably be explained by the fact that it had already entered the degassing phase earlier.

The final two combustion phases, degassing and carbonisation phase, are, however, more important as they are longer and have a larger effect on the combustion efficiency and a larger effect on health. Rooikrans (261 ppm) and vines stumps (286 ppm) released the lowest amount of CO in the degassing phase, followed by wood briquettes (303 ppm), Camelthorn (451 ppm), Black Wattle (912 ppm), Bluegum (1001 ppm) and wood pellets (1343 ppm). In the carbonation phase all the wood species showed a significant increase in CO levels. Wood pellets (2706 ppm) and Rooikrans (3081 ppm) emmited the lowest amount, followed by Black Wattle (3716ppm), vine stumps (3735ppm), Camelthorn (3963ppm) and Wood briquettes (4331ppm). Bluegum recorded a rather high CO level of 5588 ppm.

Figures 27 and 28 show the CO levels recorded during the three combustion phases for all tested biofuels.

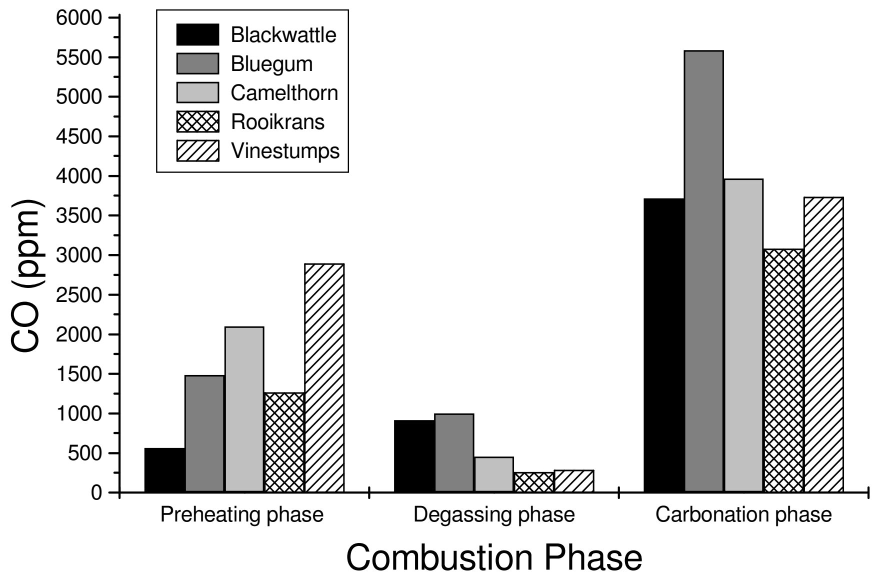


Figure 27: CO levels for the different combustion phases of woody biomass.

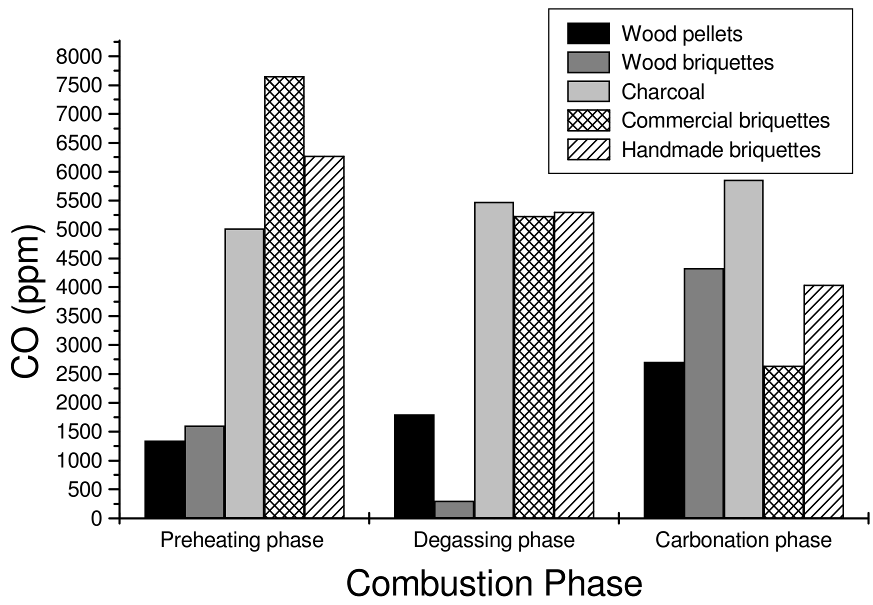


Figure 28: CO levels for the different phases of combustion of processed biomass.

The coal products did not show a notable dip in CO levels during the degassing phase. In both the final phases, the commercial briquettes performed best emitting 5235ppm and 2644ppm, respectively. This was followed by the handmade briquettes with 5310 ppm and 4047 ppm. Both products showed a steady decrease in CO emissions. The charcoal, on the other hand, had increasing CO levels over the three phases rising from 5017 ppm to 5858 ppm.

Table 6 shows the CO levels of all biofuels through the three combustion phases:

| | Preheating phase | Degassing phase | Carbonisation phase |
|---|---|---|---|
| Black Wattle | 563 | 912 | 3716 |
| Bluegum | 1484 | 1001 | 5588 |
| Camelthorn | 2097 | 451 | 3963 |
| Rooikrans | 1269 | 261 | 3081 |
| Vine stumps | 2892 | 286 | 3735 |
| Wood pellets | 1569 | 1343 | 2706 |
| Wood briquettes | 1606 | 303 | 4331 |
| Charcoal | 5017 | 5482 | 5858 |
| Commercial briquettes | 7657 | 5235 | 3644 |
| Handmade briquettes | 6276 | 5310 | 4047 |

Table 6: CO levels in the three combustion phases in parts per million (ppm)

Carbon monoxide is both an environmental and health hazard. CO emissions do not play a large role in high efficiency combustion on an industrial scale, but heavily affect rural communities using wood and coal for heat and cooking – sometimes even inside the house. If an open fire is used in an enclosed area, CO poisoning can be deadly, as it is extremely toxic. Although CO levels can be reduced by efficient combustion, the majority of informal cooking setups do not cater for good airflow and high combustion rates, causing CO levels to rise drastically in the carbonisation phase.

Overall the coal products performed worse than the woody biomass, because charcoal and coal briquettes burnt at lower temperatures due to the much lower volatile mater content. This means that not enough energy is produced to combine the CO released from the coal with atmospheric $O_2$ to form $CO_2$. As a result the CO levels are very high.

Black Wattle and Rooikrans performed best in the overall CO emission. Wood briquettes released significantly less CO in the carbonisation phase than any other fuel, making it an ideal replacement for coal in an informal setup.

### 4.3.2 Carbon dioxide

Figures 29 and 30 show the $CO_2$ levels recorded during the different phases of combustion.

The $CO_2$ level together with the amount of oxygen is a good indicator for the combustion efficiency. Low $CO_2$ levels generally mean that there is too much oxygen in the system, which may cause heat and energy loss. This is also marked by high CO levels. It is better to have high $CO_2$ and low $O_2$ and CO levels, which means that combustion is taking place more efficiently. The degassing and carbonation phase are again more important, as they are indicative of the efficiency that these materials combust with.

Looking at the wood products in the degassing phase the wood pellets performed best with 7.99% $CO_2$, followed by Black Wattle (7.7%), Bluegum (6.53%), wood briquettes (5.98%), Camelthorn (5.57%), vine stumps (5.2%) and Rooikrans (4.74%). In the carbonation phase the $CO_2$ levels dropped considerably with the sharp decline in temperature. The lower temperatures decreased the amount of volatile gasses which could combine with oxygen.

In the carbonisation phase Bluegum had the highest $CO_2$ level of 2.14%, followed by Black Wattle (2.13%), Camelthorn (2.05%), vine stumps (1.91%), wood briquettes (1.84%), wood pellets (1.83%) and Rooikrans (1.59%).

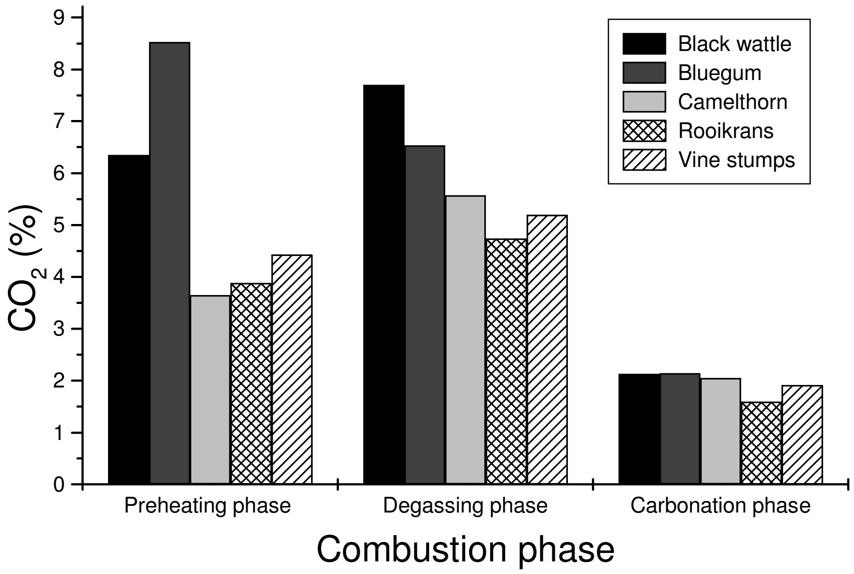


Figure 29: $CO_2$ levels for the different phases of combustion of woody biomass.

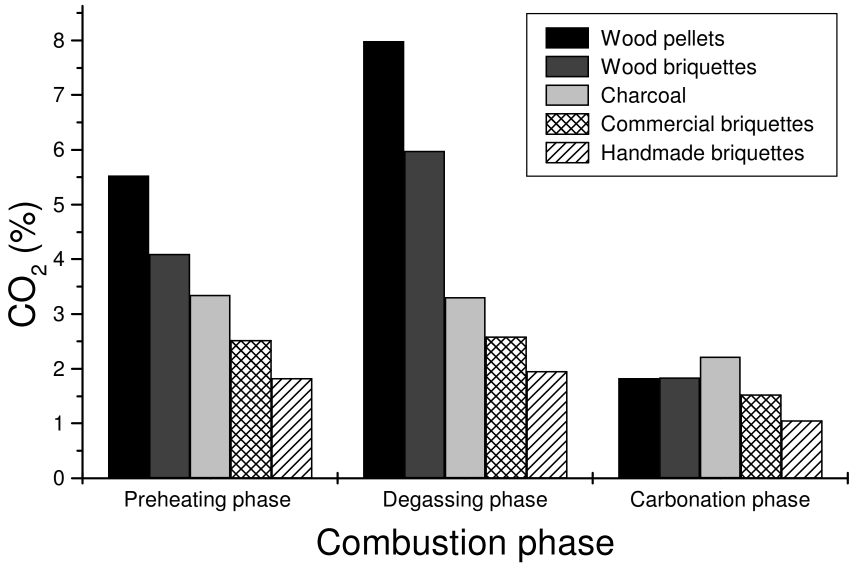


Figure 30: $CO_2$ levels for the different phases of combustion of processed biomass.

| | Preheating phase | Degassing phase | Carbonisation phase |
|---|---|---|---|
| Black Wattle | 6.35 | 7.7 | 2.13 |
| Bluegum | 8.53 | 6.53 | 2.14 |
| Camelthorn | 3.65 | 5.57 | 2.05 |
| Rooikrans | 3.88 | 4.74 | 1.59 |
| Vine stumps | 4.43 | 5.2 | 1.91 |
| Woodpellets | 5.53 | 7.99 | 1.83 |
| Wood briquettes | 4.1 | 5.98 | 1.84 |
| Charcoal | 3.35 | 3.31 | 2.22 |
| Commercial briquettes | 2.52 | 2.59 | 1.53 |
| Handmade briquettes | 1.83 | 1.96 | 1.06 |

Table 7: $CO_2$ levels in the three combustion phases in percentage

The coal products showed a relatively low decrease over the three combustion phases. This is also indicated by the high levels of CO mentioned above. Charcoal burnt with the best efficiency and had $CO_2$ levels of 3.35%, 3.31% and 2.22, followed by commercial briquettes with 2.52%, 2.59% and 1.53% and finally the handmade briquettes showed the worst combustion performance with the lowest $CO_2$ levels of 1.83%, 1.96%, and 1.06%.

From an environmental point of view $CO_2$ emissions should be as low as possible, which is enforced by most governments these days. In industrial setups the combustion efficiency is typically high and $CO_2$ emissions are sometimes reduced by feeding wood products together with coal (co-firing). I this case the both Rooikrans and vine stumps, which emitted lower amounts of $CO_2$, than the wood pellets and wood briquettes normally used for these purposes, would be good candidates. However, taking into account size uniformity and transportation costs, the engineered products may be the better option. Considering the environmental impact, Bluegum would be the worst choice for industrial combustion.

## 4.4 Rating

Table 8 shows a rating of all tested biofuels, taking the characteristic values determined from the time/temperature profiles and emission values into account. For each criterion a value between one and ten was assigned with 1 being the best and 10 being the worst. For example, for $T_{max}$ and $T_{coal}$, the highest temperature was allocated 1 and the lowest 10. For t to $T_{max}$ the fastest biofuel was given the best value because of its quick ignition. For t to $T_{coal}$, on the other hand, the slowest biofuel was given the best value, because of its long burning time before the flames died out. For the coal temperature decline rate the slowest rate received a 1 and the fastest a 10.

For the flue gas determination an average value was determined for the three combustion phases. For both CO and $CO_2$ larger emission values were regarded as negative, even though large $CO_2$ levels are a sign for efficient combustion. Nevertheless, it is a greenhouse gas and can cause health problems and death at excessive exposures.

| | $T_{max}$ Channel 1 | $T_{max}$ Channel 3 | $T_{coal}$ Channel 1 | $T_{coal}$ Channel 3 | t to $T_{max}$ Channel 1 | t to $T_{max}$ Channel 3 | t to $T_{coal}$ Channel 1 | t to $T_{coal}$ Channel 3 | Coal decline Channel 1 | Coal decline Channel 3 | Av. CO | Av. $CO_2$ | Average Mark |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Camelthorn | 3 | 3 | 4 | 2 | 4 | 4 | 6 | 6 | 6 | 6 | 2 | 10 | 4.67 |
| Black Wattle | 4 | 2 | 3 | 4 | 6 | 3 | 8 | 9 | 9 | 9 | 7 | 9 | 6.08 |
| Bluegum | 2 | 1 | 1 | 1 | 1 | 1 | 9 | 10 | 10 | 10 | 5 | 5 | 4.67 |
| Rooikrans | 5 | 4 | 8 | 8 | 5 | 7 | 7 | 5 | 5 | 4 | 1 | 4 | 5.25 |
| Vine stumps | 1 | 7 | 2 | 6 | 2 | 2 | 10 | 7 | 8 | 8 | 6 | 6 | 5.42 |
| Wood pellets | 6 | 5 | 6 | 3 | 3 | 6 | 5 | 8 | 7 | 7 | 3 | 8 | 5.58 |
| Wood briquettes | 9 | 6 | 10 | 9 | 7 | 5 | 4 | 4 | 2 | 2 | 4 | 7 | 5.75 |
| Commercial charcoal | 7 | 8 | 5 | 5 | 9 | 8 | 2 | 2 | 4 | 5 | 9 | 3 | 5.58 |
| Commercial briquettes | 10 | 9 | 7 | 7 | 10 | 10 | 1 | 1 | 3 | 3 | 10 | 2 | 6.08 |
| Handmade briquettes | 8 | 10 | 9 | 10 | 8 | 9 | 3 | 3 | 1 | 1 | 8 | 1 | 5.92 |

Table 8: Rating of all tested biofuels with the average mark.

The biofuel with the lowest average was the best performing, which was Camelthorn and Bluegum at 4.67, followed by Rooikrans (5.25), vine stumps (5.42), wood pellets and commercial charcoal (5.58), wood briquettes (5.75), handmade briquettes (5.92) and finally the Back wattle and commercial briquettes with (6.08).

# 5. Conclusions

The aim of this project was to construct and test a combustion unit to obtain time/temperature profiles for different biofuels commonly used in South Africa - both formally and informally. Parameters were determined for temperatures, as well as some flue gas emissions. The constructed unit made provision for the insertion of thermocouples at four different positions above the base of the fire, allowing temperature readings every three seconds. This yielded a characteristic combustion profile for each biofuel. The chimney allowed the insertion of a probe to extract flue gas and measure CO and $CO_2$ levels, which describe the combustion. The characteristic values used to describe each biofuel were the maximum temperature ($T_{max}$), coal forming temperature ($T_{coal}$), the time it took to reach maximum temperature (t to $T_{max}$), the time it took to reach coal forming temperature (t to $T_{coal}$), the time it took from coal forming temperature until it reached 80°C (t $T_{coal}$ to 80°C) and finally the coal decline rate. These values were used to compare the different biofuels and rate them according to different end uses.

Rooikrans (invasive) and Camelthorn (native) were the best suited for small scale heating and cooking purposes. They achieved good combustion temperatures in the degassing phase and slow rates of temperature decline in the carbonization phase, which provided sufficient heat for cooking. From the processed products the wood briquettes gave good results with a long degassing phase, which is ideal for heating and a slow coal decline rate making it a good cooking option.

For industrial use the wood pellets and charcoal did not necessarily give the best results, but the fact that they are engineered to be ideally suited for combustion in furnaces and boilers makes them the most favourable option. The woody biomass tended to have more erratic combustion profiles caused by the non-uniformity of wood, which is not ideal for large scale usage.

Charcoal outperformed both the commercial and the handmade briquettes. Their only disadvantage is their low density requiring larger volumes for combustion, but they are cheap to produce.

The highest CO emission took place in the carbonation phase, when airflow is reduced. Overall the coal products performed worse than woody biomass, with the CO levels of charcoal increasing in time. Black Wattle and the Rooikrans showed the lowest CO emissions.

The $CO_2$ emission need to be seen from two perspectives: on the one hand it is a greenhouse gas and its emissions need to be reduced worldwide. On the other hand it is an indicator for combustion efficiency - the higher the $CO_2$ level, the more efficient the combustion process. Wood pellets had the highest $CO_2$ emission, showing good combustion efficiency and proving its worth as a popular industrial energy source.
From and environmental point of view Rooikrans and vine stumps showed the lowest emissions.

The overall rating suggests that Camelthorn and Bluegum are best biofuel to consider, but both are slow growing and less abundant than other species, like Rooikrans or Black wattle. Camelthorn is also protected by law and no live tree is allowed to be harvested, making it the most unsustainable option.

Rooikrans showed the best results as biofuel for informal household cooking and heating. It rated third overall and together with the fact that it is readily available in the coastal regions and extremely invasive (i.e. needs to be cleared) it should be used more effectively.

Wood briquettes performed quite well, too. They are easy and cheap to manufacture and can be made from most types of woody residues. Their manufacture would be a good option for future government development projects.
Charcoal showed good combustion characteristics, but emissions were higher than in woody biomass, making it better suited for industrial use where filtering and cleaning technology is in place.

Some of these fuels are only used in certain areas, for example Cammelthorn in the Northern Cape, Rooikrans in the coastal areas and Black wattle in the northern provinces. Thus recommendations for further study would lie in an analysis of these biofuels for different regions. With regards to environmental impact the harvesting of fire wood could be studied and its impact on the surrounding fauna and flora in order to identify areas that might need urgent attention and are at risk for future ecological problems.

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# 7. Appendix

Appendix : Design of the combustion chamber

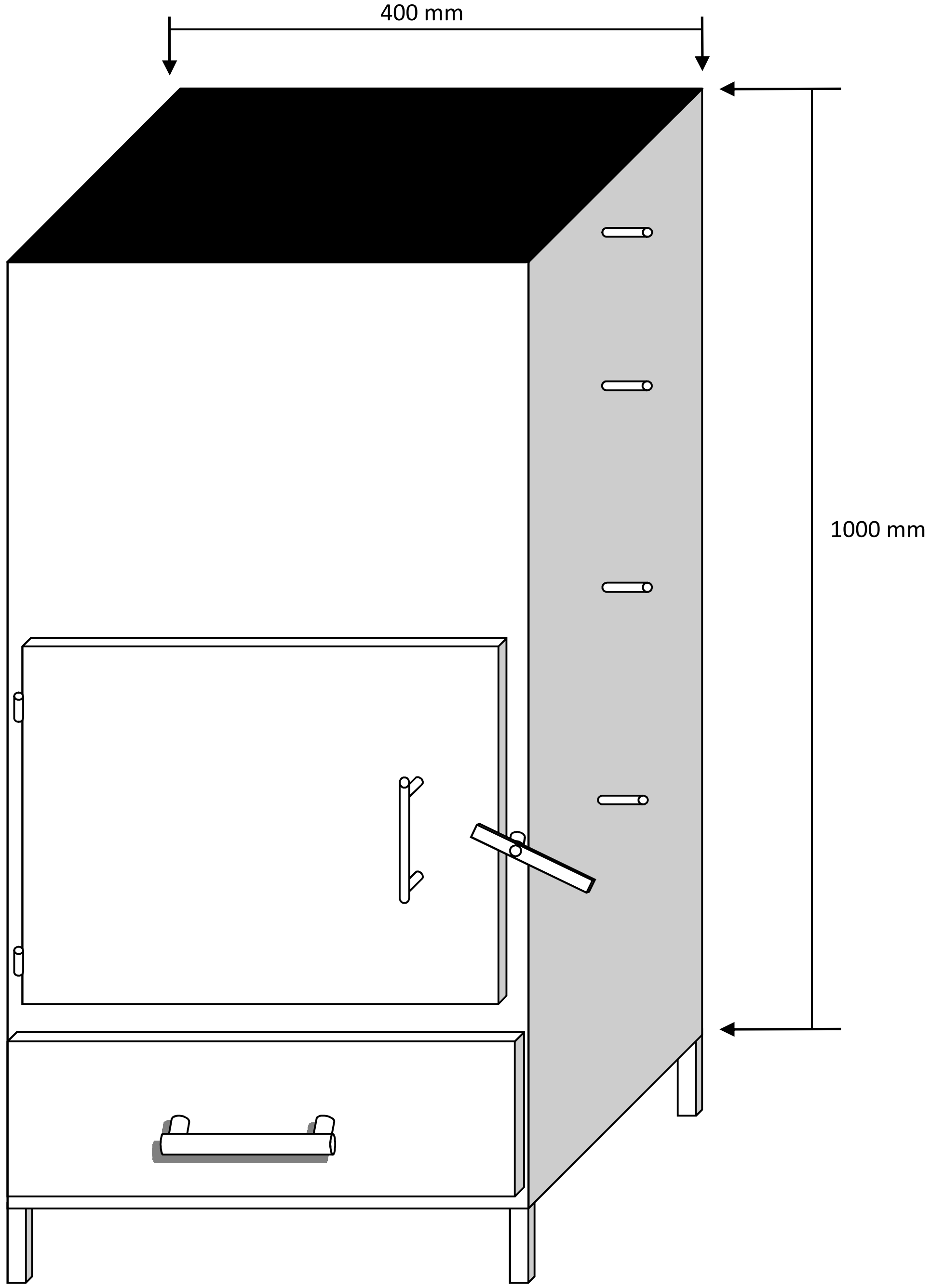


Figure 31: Isometric view of combustion box.

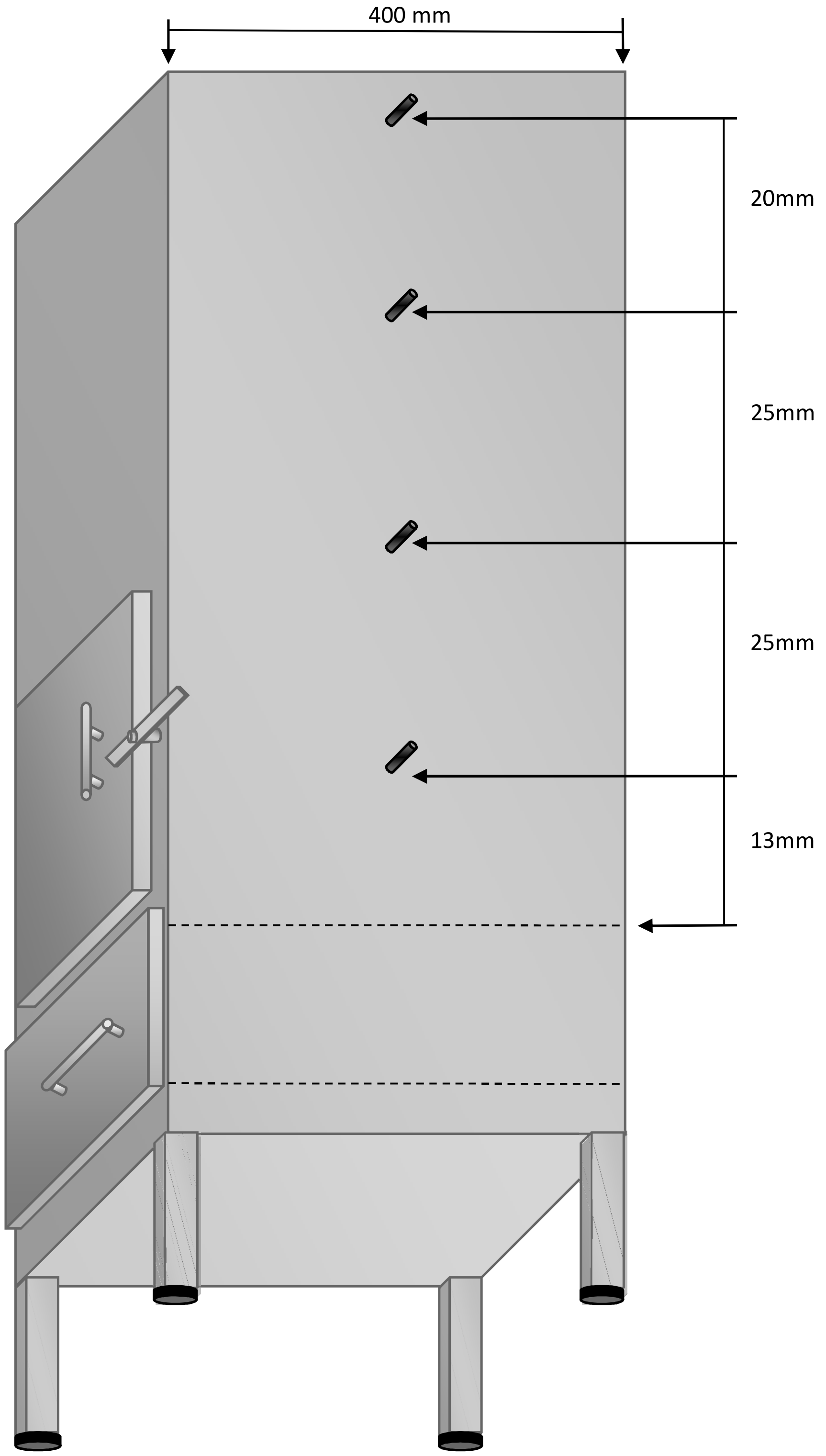


Figure 32: Isometric view indicating the thermocouple inserts and their height from the base of the fire.

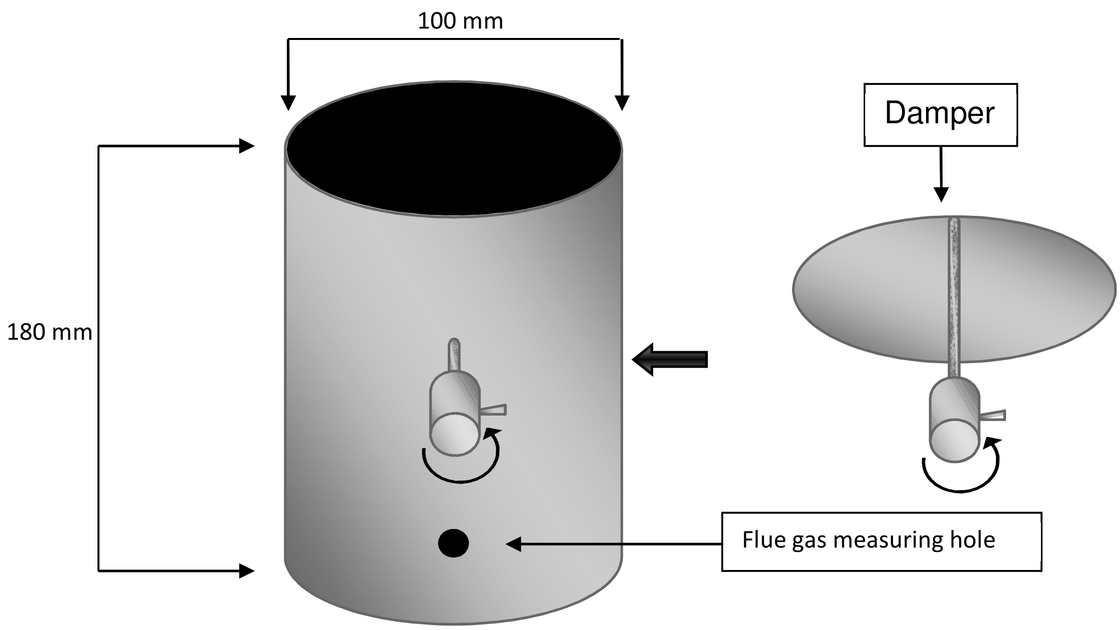


Figure 33: Chimney outlet with damper used for airflow control and flue gas extraction hole.

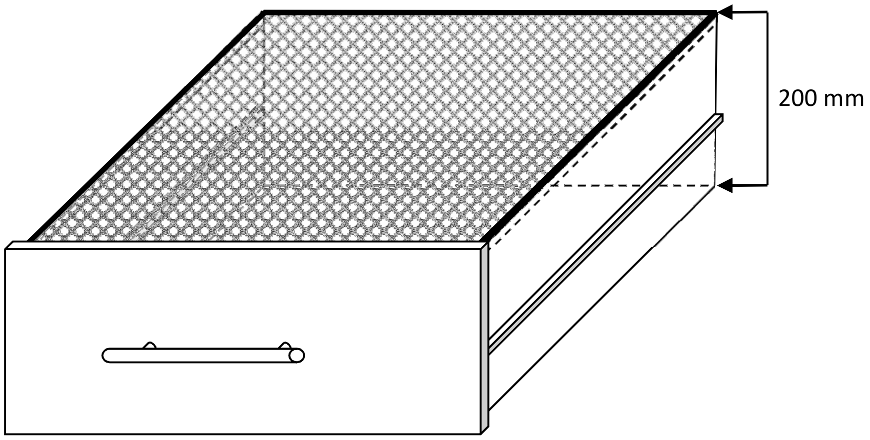


Figure 34: Drawer with grid on which biomass is combusted**.**